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# The geology of Hotei Regio, Titan: Correlation of Cassini VIMS and RADAR

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ABSTRACT

Joint Cassini VIMS and RADAR SAR data of ~700-km-wide Hotei Regio reveal a rich collection of geological features that correlate between the two sets of images. The degree of correlation is greater than anywhere else seen on Titan. Central to Hotei Regio is a basin filled with cryovolcanic flows that are anomalously bright in VIMS data (in particular at 5 μm) and quite variable in roughness in SAR. The edges of the flows are dark in SAR data and appear to overrun a VIMS-bright substrate. SAR-stereo topography shows the flows to be viscous, 100–200 m thick. On its southern edge the basin is ringed by higher (~1 km) mountainous terrain. The mountains show mixed texture in SAR data: some regions are extremely rough, exhibit low and spectrally neutral albedo in VIMS data and may be partly coated with darker hydrocarbons. Around the southern margin of Hotei Regio, the SAR image shows several large, dendritic, radar-bright channels that flow down from the mountainous terrain and terminate in dark blue patches, seen in VIMS images, whose infrared color is consistent with enrichment in water ice. The patches are in depressions that we interpret to be filled with fluvial deposits eroded and transported by liquid methane in the channels. In the VIMS images the dark blue patches are encased in a latticework of lighter bands that we suggest to demark a set of circumferential and radial fault systems bounding structural depressions. Conceivably the circular features are tectonic structures that are remnant from an ancient impact structure. We suggest that impact-generated structures may have simply served as zones of weakness; no direct causal connection, such as impact-induced volcanism, is implied. We also speculate that two large dark features lying on the northern margin of Hotei Regio could be calderas. In summary the preservation of such a broad suite of VIMS infrared color variations and the detailed correlation with features in the SAR image and SAR topography evidence a complex set of geological processes (pluvial, fluvial, tectonic, cryovolcanic, impact) that have likely remained active up to very recent geological time (<$10^4$ year). That the cryovolcanic flows are excessively bright in the infrared, particularly at 5 μm, might signal ongoing geological activity. One study [Nelson, R.M., and 28 colleagues, 2009. Icarus 199, 429–441] reported significant 2-μm albedo changes in VIMS data for Hotei Arcus acquired between 2004 and 2006, that were interpreted as evidence for such activity. However in our review of that work, we do not agree that such evidence has yet been found.

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## 1. Introduction and background

Hotei Regio (IAU formal name for a ~700-km-wide region centered at 78°W 26°S) has been flagged as an enigmatic region on Titan in various analyses of Cassini visible-light, short-wavelength-infrared, and radar observations. Hotei Arcus (also an IAU formal name) is a bright arc that forms the southern margin of Hotei Regio; we further clarify this distinction in Section 2. A consensus is emerging that Hotei Regio is a geologically young cryovolcanic region. Cryovolcanism is a term used to describe viscous flow of molten, low-density, low melting-point materials that form the crusts and interiors of the icy satellites of the outer Solar System. One

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type, ammonia–water–hydrate volcanism (eutectic melting point of 176 K, cf. Lewis, 2004), has long and recently been suggested to occur on Titan (cf. Stevenson, 1992; Mitri et al., 2008). An attractive feature of ammonia–water–hydrate is its moderate viscosity, which allows the development of thick flows (cf. Kargel et al., 1991). However, the material's drawback is its relatively high density (similar to liquid water), which hampers buoyant migration to the surface through a largely water–ice crust. Methane–clathrate–hydrate volcanism has also been suggested (cf. Tobie et al., 2006). This material has lower density, so its access to the surface is easier, but on reaching the surface it would probably explosively decompose into liquid methane and water ice (Lunine and Stevenson, 1987)—thick viscous flows would not be a likely result. Finally Fortes and Grindrod (2006) have suggested mud volcanism, in which acetylene (a low density organic solid at Titan's surface) is saturated with liquid methane forming muddy slurries. Although the form(s) of Titan's cryovolcanic flows remain in question, Cassini SAR images (2.17-cm synthetic aperture radar images from the Cassini Titan radar mapper) provide ample evidence for cryovolcanic flows in numerous regions on Titan (Lopes et al., 2006).

Wall et al. (2009) provide compelling evidence from SAR images that central Hotei Regio is a depression filled with cryovolcanic flows and surrounded by higher, mixed rough and smooth terrain. In addition, they describe a series of fluvial channels, thought to have been carved by liquid methane, that evidence flow down from south-bounding surrounding mountains to the margins of the volcanic-filled depression. Stereogrammetric analysis of the SAR images confirms that the Hotei Regio flows are in fact in a depression ~1 km below the bounding mountains to the south, and that individual flows are 100–200 m thick (Kirk et al., 2009). In this paper we add to this geological picture the analysis of recent VIMS (Cassini visual and infrared mapping spectrometer; Brown et al., 2004) spectral image cubes of the Hotei Regio that show patterns of surface compositional variations and regional-scale geologic structures and features, many of which bear striking correlations with those seen in the SAR data.

Barnes et al. (2005, 2006) described Hotei Regio as one of two regions (the other being Tui Regio) that stands out from the rest of Titan as anomalously bright at 5 μm in VIMS images. Hotei Regio and Tui Regio are likely similar regions geographically and geologically; both are located in the 20°S–30°S latitude zone along the southern margin of continental-sized bright region, Xanadu. They both exhibit features suggestive of volcanic flows (Barnes et al., 2006; Wall et al., 2009), are of comparable scale (each hundreds of kilometers across), and exhibit very similar spectral properties, most notably their much higher 5-μm reflectivity than anywhere else on Titan (Barnes et al., 2007).

Firm spectroscopic evidence for the composition of these regions has been elusive. $CO_2$ ice, expected at the surface from comet impacts (e.g. Kress and McKay, 2004) and in evidence in the Huygens Gas Chromatograph Mass Spectrometer surface data (Niemann et al., 2005), is an interesting possibility for the materials of these 5-μm-bright spots. Barnes et al. (2005) speculated that the materials in Hotei Regio and Tui Regio could be eroded layers or recent deposits of $CO_2$. McCord et al. (2006, 2008) described VIMS spectroscopic evidence for $CO_2$. They noted that in the VIMS data, in addition to being bright at 5 μm, these features exhibit excess brightness at 2.8 μm (particularly when compared to their average brightness at 2.7 μm) and a spectral absorption feature at 4.92 μm, all of which might be attributed to fine-grained $CO_2$ ice. However the 4.92-μm feature is substantially shifted (by ~25 nm) from the spectral position of the $CO_2$ feature seen in the laboratory, making the identification less convincing. Clark et al. (submitted for publication) suggest that cyanoacetylene ($HC_3N$) provides a much better spectral match for the 4.92-μm absorption. This compound is a known photochemical product in Titan's thermosphere and lower atmosphere and was detected by Voyager IRIS and Cassini CIRS and INMS (Kunde et al., 1981; Coustenis et al., 2007; Waite et al., 2008). Its production rate is on order of 1 m/Gyr. If cyanoacetylene is present at the surface in Tui Regio (and at Hotei Regio by implication) the unanswered question remains as to what geological process could be responsible for its concentration.

Prior VIMS studies of Hotei Regio by necessity used low-resolution (>30 km/pixel) views. In this paper we explore the first moderate-resolution VIMS observations of Hotei Regio, from Cassini's T47 November 2008 Titan flyby. We first describe the observations and their reduction and analysis using radiative transfer modeling. Next we overlay the VIMS and RADAR views of the area, showing their strong correlation. We then provide a set of geologic interpretations of the combined datasets.

## 2. VIMS observations and photometric analysis

The VIMS spectral images described here were acquired on 11/19/2008 during Cassini's T47 flyby of Titan. Five cubes (CM_1605796665-8513) were acquired of Hotei Regio with resolutions increasing from 18.5 to 12.5 km/pixel. Fig. 1 shows a color mosaic of these data along with individual spectral images for each of eight methane windows taken from the highest-resolution cube (that fortuitously also covers central Hotei Regio). These VIMS cubes were acquired close to the terminator. For the area of the mosaic shown in Fig. 1 the ranges of incidence and emission angles are $i \sim 50–90°$ and $e \sim 0–40°$; the highest-resolution cube (shown for eight methane windows in Fig. 1) exhibits somewhat smaller variation: $i \sim 64–84°$ and $e \sim 0–26°$. Consequently most of the intriguing features described in this paper found in and around central Hotei Regio were acquired at quite large solar incidence angles.

The images in Fig. 1 represent relative surface albedo, modeled as follows. The MODTRAN™ 5 radiative transfer code (developed collaboratively by Air Force Research Laboratory and Spectral Sciences, Inc.; cf. Berk et al., 2006) was used to model, for each methane window, the expected total flux ($I/F$ or radiance factor) that would be observed by VIMS as a function of the albedo of an ideal Lambertian surface, computed over a wide range of incidence and emission angles. We used the 8-stream DISORT mode (Discrete Ordinates Radiative Transfer), correlated-k absorption coefficients for $CH_4$ from Irwin et al. (2006), optical constants for laboratory tholins formed in cold plasma from Imanaka et al. (2004, 2005), and following Griffith et al. (2006), collision-induced absorption of $N_2$ and $H_2$ from McKellar (1989) (this affects the long-wavelength side of the 2.0-μm $CH_4$ window). Following the direction of Tomasko et al. (2005) in modeling Titan's aerosols as particle clusters, we used a T-Matrix code (cf. Mishchenko et al., 1994) to model nonspherical aerosol aggregates as 256 particle clusters of 50-nm monomers using optical constants of the darker of two tholins described in Imanaka et al. (2005). We also adopted the vertical aerosol haze profile used by Tomasko et al. (2005).

The output of the MODTRAN™ 5 radiative transport model yields a series of numerical predictions of the form $I/F(\lambda, \mu, \mu_0) = R_L(\lambda, \mu, \mu_0)$, where $R_L$ is the model albedo of a Lambertian surface and $\mu_0$ and $\mu$ are cos($i$) and cos($e$), respectively. These models were then fitted to a set of analytical functions of the form: $R_L(\lambda, \mu, \mu_0) = f[I/F(\lambda, \mu, \mu_0)]$. Owing to uncertainties in many of the inputs used in the MODTRAN™ 5 radiative transfer model (e.g. gas absorption coefficients and the vertical variation, size distribution, and optical properties of the aerosols) these models do generally, but not precisely, predict the VIMS observed variations in $I/F$ versus incidence and emission. However, they do provide a good sense of the expected functional behavior of this dependence. To further

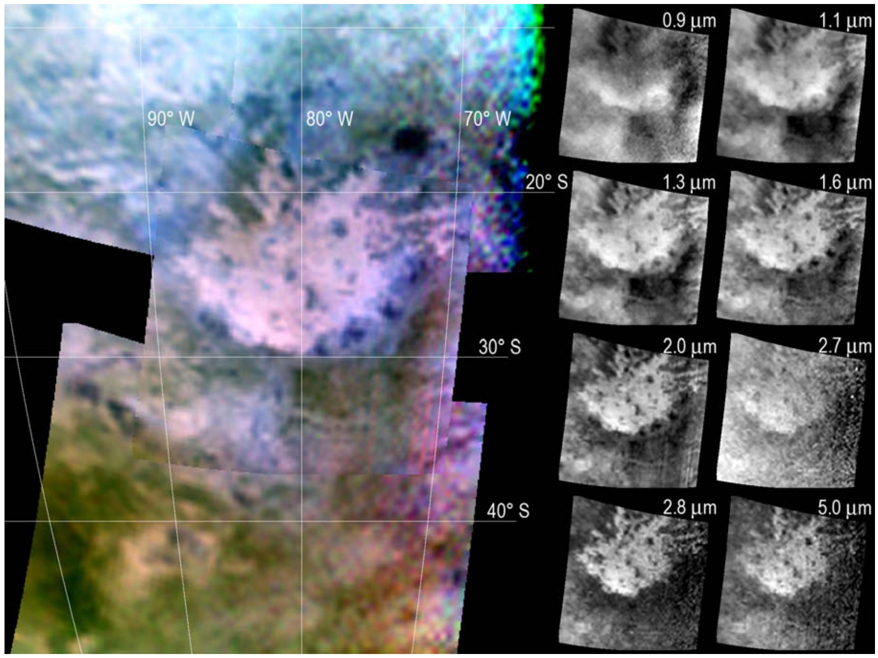


**Fig. 1.** Photometrically derived VIMS albedo images using a radiative transfer model: (left) mosaic of five VIMS cubes with color composite RGB = 2.0, 1.6 and 1.3 μm and (right) central spectral image cube of the mosaic (also highest resolution VIMS cube of Hotei Regio) shown in spectral bands for each of eight methane atmospheric windows.

constrain the models we used multiple VIMS observations of individual surface targets that were acquired over a variety of photometric angles ($\mu$ and $\mu_0$). The final fitted functions were then used to "invert" the observed $I/F(\lambda)$ into maps of model surface albedo; the results are shown in Fig. 1. Owing to uncertainties in this procedure, the model albedos should be considered relative albedos (their absolute values being most uncertain).

Given all of these caveats, the uniformity in brightness and contrast across the eight individual methane window images (Fig. 1) gives testimony, at least in a relative sense, to the efficacy of the procedure. The uncertainties are greatest at shorter wavelengths where the haze opacity is highest. For example, for the case of a Lambertian surface albedo of 0.05 under vertical illumination and emission, the modeled fraction of the observed beam reflected from the surface that passes unscattered to the spacecraft through the atmosphere is ~2% at 0.9 μm, ~56% at 2.0 μm, and ~90% at 5.0 μm. As the surface is partly illuminated by multiply scattered radiation, including scattering between surface and atmosphere, these fractions are functions of the surface albedo itself. Results for the 2.7- and 2.8-μm windows are the poorest because although aerosol scattering is much lower relative to shorter wavelengths, there is substantial uncertainty in atmospheric absorptions between 2.5 and 3.5 μm and the model results are quite poor. Because of the rapid fall off in scattering with increasing wavelength, the estimated albedo at 5.0 μm is by far the most reliable. We estimate the 5-μm albedo of parts of the bright material in Hotei Regio to be as high as 0.12. We estimate other Titan bright regions (other than Tui Regio) have albedos ~0.03–0.05 and dark regions 0.02–0.03. Ontario Lacus, a south polar hydrocarbon lake was found by Brown et al. (2008) to have a 5-μm albedo $\leqslant$0.001.

Many intriguing features are evident in the eight spectral albedo images of central Hotei Regio. Contrast varies markedly with wavelength. For example a darker zone just SE of Hotei Regio falls off in contrast from 1.1 μm to 2.0 μm whereas bright, narrow, arcuate patterns that lace it increase in contrast over this range. A series of small, isolated, dark spots around the southern margin of Hotei Regio are darkest at 1.6 μm and 2.0 μm. Because they are relatively brighter at 1.3 μm, they appear dark blue in the mosaic (RBG = 2.0, 1.6, 1.3 μm). These exhibit the same spectral character as the "dark blue" unit of Soderblom et al. (2007b) noted to be consistent with an increased concentration of water ice (which absorbs strongly at these wavelengths). A feature earlier dubbed the "Smile" (now formally named Hotei Arcus), most evident in the 0.9-μm and 1.1-μm images in Fig. 1, appears as a bright arc just inside the southern margin of Hotei Regio. This feature was first imaged at 1.6 μm with adaptive optics on the Keck II telescope (Roe et al., 2004) and was clearly visible as a bright arc in an ISS image (Cassini Imaging Science Subsystem) acquired in the 0.9-μm window in December 2004 (Barnes et al., 2005). Barnes and colleagues commented that this feature might denote a "heavily eroded crater, although the old crater idea does not explain why 'the Smile' is so bright. The feature's symmetry seems to imply structural control. The ISS image shows a crenulated margin, perhaps due to surface flows or erosion". From the discussions that follow we shall see that these early notions were remarkably perceptive.

## 3. Mapping: correlations between VIMS and SAR

In general, Titan's surface features as seen in VIMS and SAR images are only weakly correlated (Soderblom et al., 2007b); VIMS senses the composition of the upper few tens of microns of the surface, while SAR is sensitive to surface roughness and the scattering properties of the upper meter or so of the surface. The notable exceptions to this weak correlation are vast belts of longitudinal dunes (Lorenz et al., 2006; Radebaugh et al., 2008) whose patterns are strongly correlated in VIMS and SAR data (Barnes et al., 2007, 2008; Soderblom et al., 2007b). The dunes are radar-dark and optically dark in VIMS images and exhibit VIMS spectral properties consistent with water–ice-poor materials enriched in dark hydrocarbons (Soderblom et al., 2007b). As described in what follows, unlike most of Titan, Hotei Regio exhibits patterns in VIMS and SAR images that are strikingly well correlated and exhibit many detailed complex geological relationships.

The area of common coverage between the T47 VIMS images and the T41 SAR image (obtained February 2008; described by

Wall et al., 2009) is shown in Fig. 2; enlargements in Fig. 3 provide more detailed views. As mentioned earlier, the geologic model presented by Wall et al. (2009) from analysis of SAR images of Hotei Regio (cf. Fig. 3 bottom) is that of a lowland field of cryovolcanic flows surrounded by higher terrains exhibiting mixed rugged and smooth textures. Several rough, radar-bright drainage channels (likely carved by liquid methane, cf. Tomasko et al., 2005; Lorenz et al., 2008a) were interpreted by Wall et al. (2009) to have flowed down-slope, out of the higher terrain, inward toward the center of Hotei Regio, disappearing at the margin of the flow field.

Also inset in Fig. 2 is a topographic map of part of this region, compiled stereogrammetrically by Kirk et al. (2009) from a pair of SAR image swaths from Cassini Titan flybys T41 and T43 (May 2008). Red arrows in Fig. 2 denote corresponding features in the

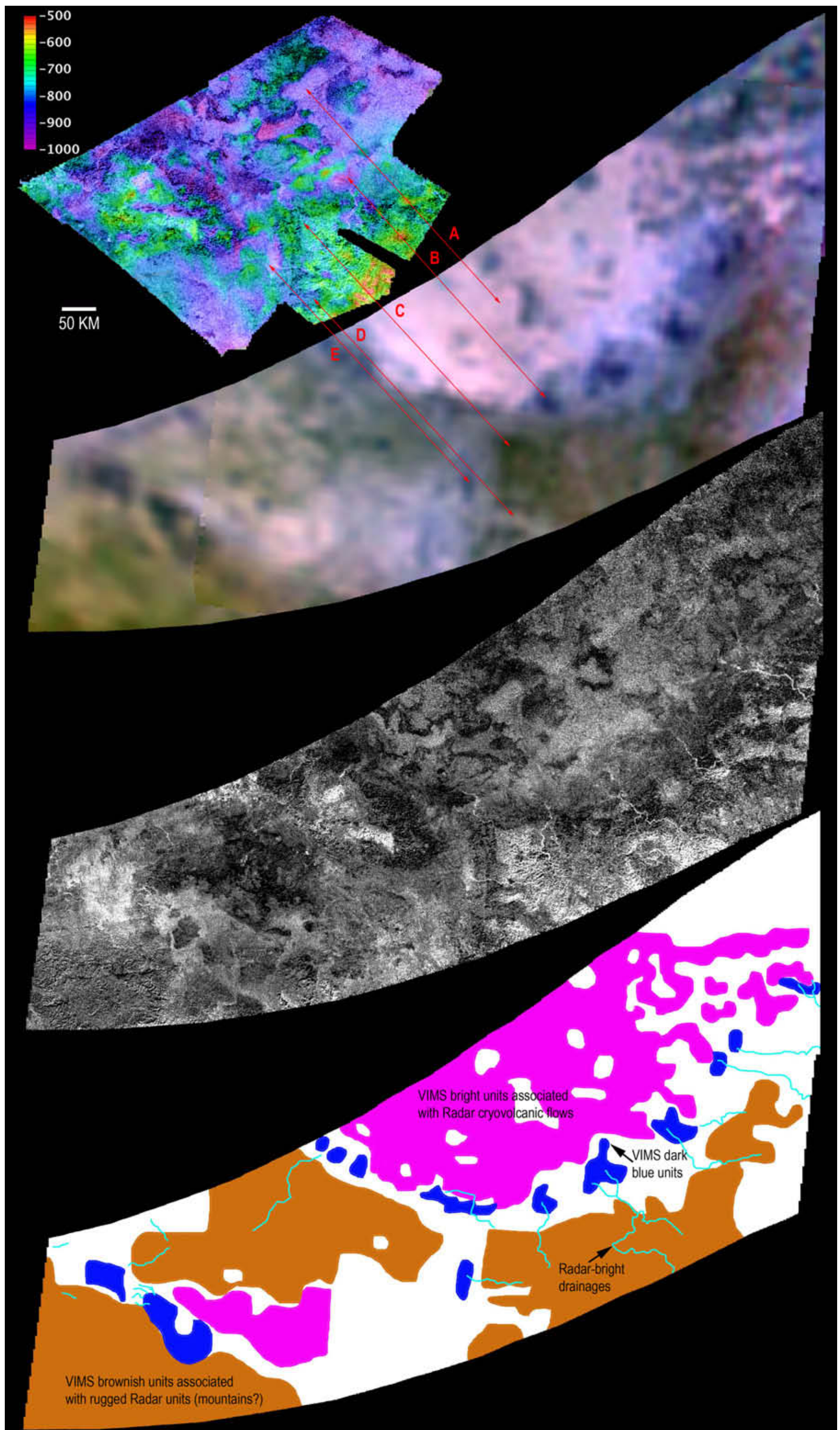


**Fig. 2.** Area of joint VIMS–SAR image coverage used to compile geologic sketch map (bottom) of central Hotei Regio. Uppermost is a Radar SAR-stereo topographic map from Kirk et al. (2009). Below it are the VIMS coverage (RGB = 2.0, 1.6, 1.3 μm) cropped from Fig. 1 and the T41 Radar SAR coverage at 128 pixels/degree (~350 m/pixel).

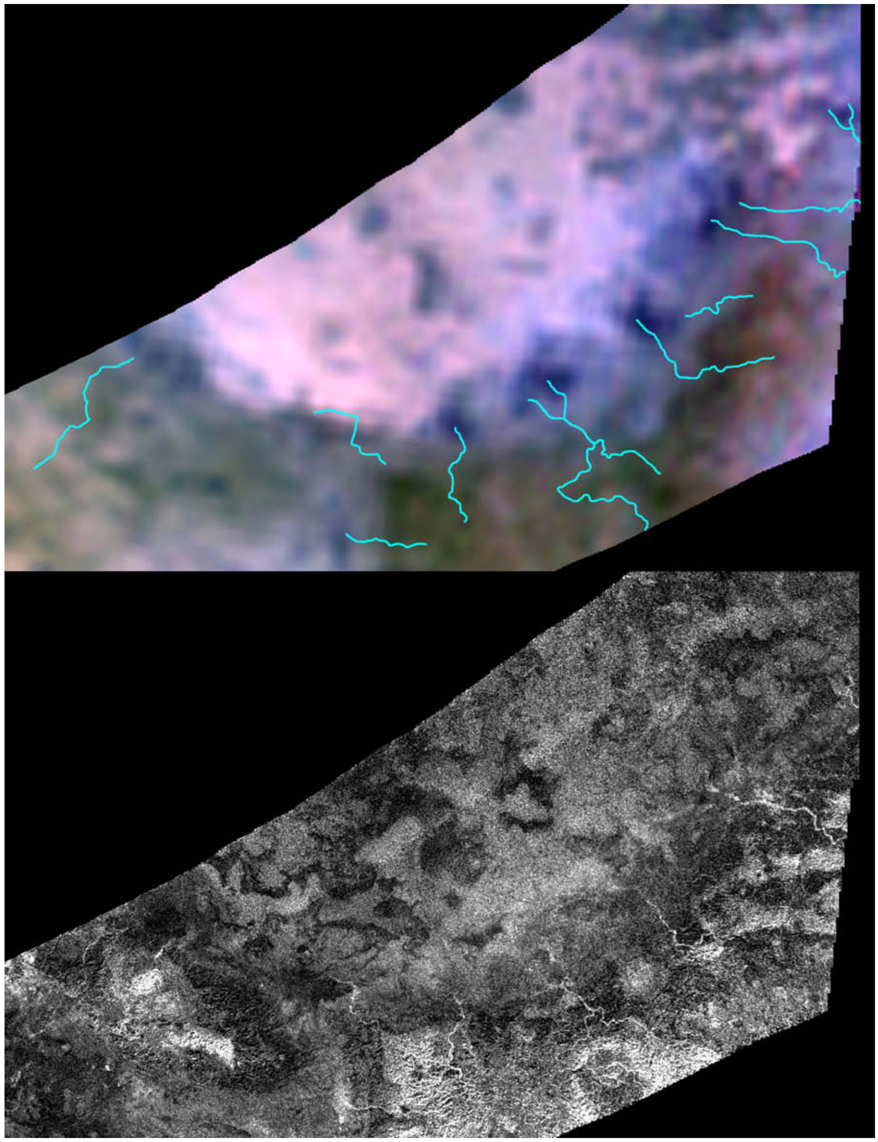

**Fig. 3.** Enlargements of parts of Fig. 2 with SAR radar-bright drainages overlaid in cyan on the VIMS (RGB = 2.0, 1.6, 1.3 μm) composite (upper) and T41 radar SAR image showing details correlations on which mapping was based (lower).

VIMS images and the SAR-stereo topography. The topographic map confirms the interpretation that central Hotei Regio (at least the part mapped) is a low basin surrounded by higher terrains around its southern margin. A good example of this high terrain is a promontory (marked C) that stands out in VIMS data as darker and brownish and in the SAR data as generally bright, rough, and rugged. The relief between the low spots in the basin and the highest mountains reaches ~1 km, typical of most of Titan's mountains (Radebaugh et al., 2007).

In general, the regions of cryovolcanic flows seen in the SAR image correspond to the VIMS bright unit that is bright at all wavelengths but particularly at 5 μm (shown as magenta in the sketch map). Most of these materials reside in the basin centered in Hotei Regio but another smaller region lies a few hundred kilometers SW. The flows are quite complex and variable; some are darker (less scattering) in the SAR image and some show lower albedo in VIMS data. Many of these variations correlate in detail. For example a lobate feature (marked A and shaped like the end of a dog bone) is among the topographically lowest features in that part of the flow field. It is bright in VIMS data and exhibits medium brightness and roughness in the SAR image. The topographic model shows it to be surrounded on the east, north, and west by flows that are 100–200 m higher that are variable in VIMS albedo (e.g. a darker flow margin to the east). When actively flowing they must have been quite viscous. The tops of the flows are quite variable but generally intermediate in radar brightness and roughness but oddly, and counterintuitive, their margins are darker in the SAR images (Kirk et al., 2009). This would suggest that the flow edges are less rough at the 2-cm scale. The flow morphology and topography suggest a flow direction generally southward around the "dog bone". Although the flows are variable in both SAR and VIMS images, in general the flows appear to overrun a substrate that is intermediate in SAR scattering and is bright in VIMS data. Additional detailed VIMS–SAR correlations along flow margins are visible in the bright stringers and irregular patterns in the easternmost part of the basin.

As described by Wall et al. (2009), the SAR image shows a series of radar-bright drainage channels around the southern perimeter of Hotei Regio (cf. Fig. 3) presumed to be carved by liquid methane (cf. Tomasko et al., 2005; Lorenz et al., 2008a). These channels are quite large, typically 100–200 km in length and 1–2 km in width, and are dendritic, branching upstream toward the higher terrain, suggesting they are pluvial, fed by methane rainfall. The topographic model shows their gradients to be ~0.5 m/km. Wall et al. (2009) concluded that they terminate at the edge of the flow field, apparently having been overrun by the younger cryovolcanics. We find to the contrary that although the channels are not resolvable in the VIMS images (resolution >12.5 km/pixel) the drainages actually terminate in a series of spots that show as dark blue in the VIMS images and lie around the southern margin of the Hotei Regio bright flows (Figs. 2 and 3). We interpret these to be fluvial deposits of detritus eroded and transported by liquid methane that flowed in the drainages. The SAR-stereo topography model shows these dark blue spots to also be local lows. One (marked B in Fig. 2) is 100–200 m below the local plain. Another (marked E), also located where a channel terminates, lies ~50 km west of the angular mountain promontory (marked C). These are dark blue in VIMS composites (RGB = 2.0, 1.6, 1.3 μm) because they are relatively darker at 2.0 μm and 1.6 μm than at 1.3 μm. This is a characteristic of water ice (strong broad absorptions centered near 1.6 μm and 2.0 μm) and led Soderblom et al. (2007b) to suggest that VIMS dark blue units are richer in water ice than the dark brown VIMS units that make up the dunes. Clark et al. (submitted for publication) caution that a variety of solid hydrocarbons that might be found at the surface of Titan exhibit spectral features that could mimic water ice as viewed through these spectrally narrow atmospheric transmission windows.

The dark blue spots around the southern margin of Hotei Regio are encased in a network of arcuate and linear bands and lanes that appear intermediate gray in the VIMS images; this network is sketched in Fig. 4. The structures are best seen and identified with most confidence along the southeast margin of Hotei Regio where four of the larger (~50 km) blue spots are located. As seen in the VIMS images (cf. Fig. 3) the rings and lanes of the gray unit found along this margin are typically 20–30 km wide extending from the base of the dark brownish mountains to the edge of the bright flows in central Hotei Regio. The pattern is suggestive of an intersecting network of circumferential and radial fault systems. The regular spacing of the four dark spots suggests radial structures (like spokes in a wheel) controlling their regular separation. Such radial and circumferential fault and fissure systems have been described around volcanic centers on Earth, Venus, and Mars (cf. Chadwick and Howard, 1991; Watters and Janes, 1995; Buczkowski, 2006). A second 25-km-wide circumferential arcuate band lies ~100 km farther out to the south (cf. Fig. 4 and arrow labeled D in Fig. 2). This band transects the mountain at D where the SAR-stereo topography model shows a lower trough that cuts through the higher terrain.

That the mountaintops are dark brown in the VIMS composites might suggest they are coated with dark organics that are poorer in water ice content as is inferred by Soderblom et al. (2007b) for the vast dune fields. The association between the SAR channels and VIMS dark blue units that are apparently the result of deposition by the channels is reminiscent of the Huygens landing site. There, DISR (Descent Imager/Spectral Radiometer) images show dendritic channels that descend from highlands areas and debouch into the dark dune-free plain where the Huygens Probe landed, also a VIMS dark blue unit (Soderblom et al., 2007a,b).

## 4. Discussion regional structures and features – speculations on origin and age

The arcuate and linear structures extend far beyond the region of joint SAR–VIMS coverage shown in Figs. 2 and 3. The larger VIMS mosaic of Fig. 1 was spatially filtered (shown in Fig. 4) to enhance structural details and further suppress regional albedo variations and residual photometric errors. The structural arcs described earlier that lie along the outer southern margin of Hotei Regio are quite evident as are the linear radial segments, in particular one that truncates the western end of the mountain promontory (marked C in Fig. 2). Farther to the north another arcuate ring is evident in Fig. 4. If these are all part of the same system, then they cover an expanse of more than a thousand kilometers; fainter rings may reside even farther out from central Hotei Regio.

The high-pass-filtered version in Fig. 4 also accentuates two very circular dark spots north of Hotei Regio. Each of these features is ~100 km in diameter; their VIMS color is consistent with a high content of water ice—as might be expected were they ammonia–water–hydrate cryovolcanics. We speculate that these may be calderas—the eruptive centers for the large field of cryovolcanic flows found in central Hotei Regio. This would be consistent with the southward flow direction around the “dog bone” that we suggest in the previous section (cf. Figs. 2 and 3). The two dark circular features are located roughly on the circular extension of the structural arcs that lies along the southern margin of Hotei Regio (adjacent to the dark blue spots). The locations of the two large dark circular spots may also be structurally controlled, as are many calderas in the Solar System. Parts of the cryovolcanic flows in the central basin mapped in Fig. 2 are darker than the rest of the field in VIMS data. It is possible that the irregular dark patterns that extend southward from the two dark spots are also dark flows. Additional SAR images and topography and higher resolution VIMS images of the northern part of Hotei Regio where the posited calderas are located would be invaluable. Hopefully additional data can be acquired in the continuing Cassini Mission extensions.

We next turn to the question of the geological origin and evolution of Hotei Regio including the hypothesized radial and circumferential structures and lowland basin filled with fields of cryovolcanic flows. A key aspect in trying to understand this regional system is its enormity. The east–west dimension of the Hotei Regio flow field is >700 km as is the north–south dimension from the southern edge of the flow field to the postulated calderas to the north. The north–south dimension between the outer structural arcs sketched in Fig. 4 is >1200 km. This approaches half of Titan’s radius (2575 km). Two possibilities for the geologic formation of the structures and basin include (1) crustal flexure, uplift, and subsidence over an enormous hot convective plume in Titan’s interior and (2) ancient circular structural scars remnant from an early large impact that later served as conduits for much more recent cryovolcanism leading to crustal down-warping from loading by cryolavas in central Hotei Regio.

Stevenson (1992) evolved a model for the Titan’s interior that after differentiation and cooling results in a (1) central rocky core (radius ~ 1900 km), (2) overlain by shells of high pressure polymorphs of water ice and water–ammonia hydrate ice (~250 km), (3) overlain by a thick (~200 km) ammonia–water ocean, (4) overlain by a layers of solid methane–clathrate–hydrate, and (5) finally overlain by a porous ice I crust possibly filled with liquid hydrocarbons. Recent models of Titan’s interior support this general view (cf. Grasset and Sotin, 1996; Tobie et al., 2005) suggesting an internal ammonia–water ocean ~500-km thick below a ~100-km rigid icy crust (Mitri and Showman, 2008). Several years of Cassini radar observations have suggested that Titan’s rotation period might be changing (resulting in a shift of longitude of several tenths of a degree) and may not be locked to its orbital period (Lorenz et al., 2008b). Tokano and Neubauer (2005) predicted that exchange of angular momentum between the dense atmosphere and surface could result in seasonal shifts in longitude. In analysis of the Cassini radar data, Lorenz et al. (2008b) concluded that this would require such a subsurface ocean to decouple the silicate core from the crust allowing it to slip.

In the case that the arcuate regional structures and basin of Hotei Regio formed over a large convective plume that developed

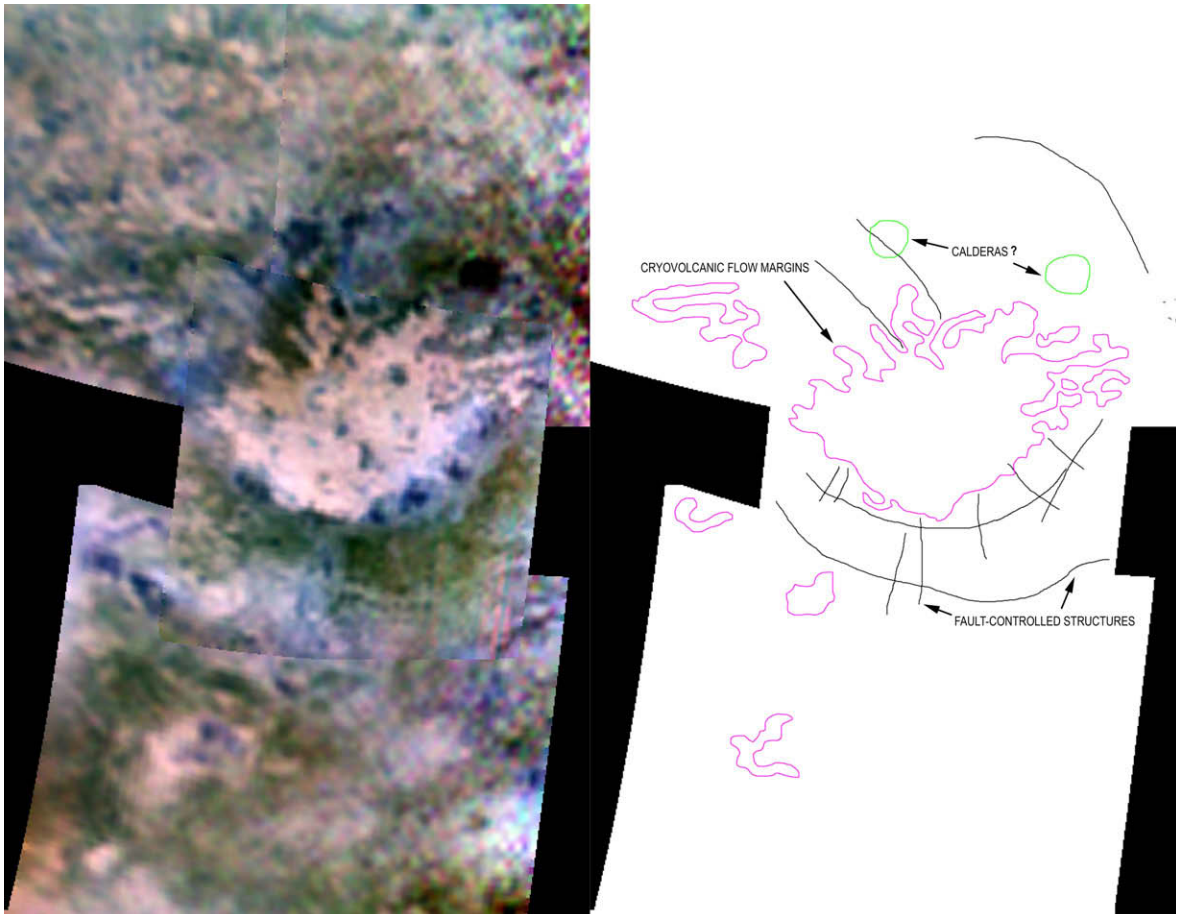


**Fig. 4.** Interpretive map showing possible calderas, fault structures and extension of the cryovolcanic flows that have characteristic patterns in VIMS data.

after differentiation, for it to have affected such a large region with such symmetry, it would have had to be extremely deep (probably >500 km). This would place it below the currently postulated internal ocean near the silicate core. This seems to be a very unlikely scenario as the plume would have had to rise intact through the hundreds of kilometers of global ocean and become tectonically coupled to the crust. For such a plume to have formed these structures during differentiation also seems unlikely because such crustal structures would probably not have survived differentiation intact.

We believe a more plausible scenario for the original formation of the regional circular structures and overall topography (consisting of a several hundred kilometer wide basin surrounded by mountainous terrains) is that they are remnant of from ancient impact basin formed post-differentiation. In addition to the outer structural arcs drawn in Fig. 4, we are struck by the circularity of the latticework of gray bands that encase the blue fluvial deposits in the depressions along the southern margin of Hotei Regio's flow field. Perhaps this low basin originated as a shallow impact basin. In this model, these ancient structures have provided conduits for geologically recent migration of cryovolcanic fluids to the surface; such eruptions could have lasted over most of Titan's geologic history. We do not suggest that the geologically younger volcanism and ancient impact basin are directly coupled, only that the impact-induced structural scars simply served as zones of weakness for the later volcanism and tectonism. We do not suggest impact-triggered volcanism. In this model the eruptive flows later filled the previously established impact basin topography, akin to the formation of the lunar maria. Crustal down-warping from the accumulating volcanics could have led to the higher-standing terrains that surround the basin or perhaps these terrains are simply eroded parts of the higher-standing crater rim.

The detailed correlations between surface topography and textures seen in the SAR image and the surface compositional variations seen in VIMS are extraordinarily well developed compared to anywhere else on Titan so far studied in this detail. The preservation of these patterns in the face of constant deposition of aerosols that continually snow out of the atmosphere suggests a geologically young surface with a wide range of processes (pluvial, fluvial, cryovolcanic, tectonic) that must have remained active up through modern geologic time. If the deposition of bright organic material (including acetylene) is 0.001–0.01 μm/year (Lara et al., 1994; Smith et al., 1996; McKay et al., 2001), the surface contrast seen by VIMS would disappear in <$10^4$ year. Whether active volcanism has actually been witnessed during the Cassini Mission is an intriguing question.

Nelson et al. (2009) reported to have observed temporal excursions in the brightness in Hotei Regio derived from VIMS observations made between mid-2004 to mid-2006. They estimated that changes in surface reflectance in the 2-μm atmospheric window by as much as a factor of two and suggested that these changes could reflect current geological activity that might be caused by surface condensations or ground fogs of some bright material that subsequently dissipates. They hypothesized that release of ammonia by ongoing, active cryovolcanism could be the explanation for the observed brightness excursions. That the expected eruptive form of ammonia is a cryovolcanic lava of a solution of ammonia and water as a monohydrate (Stevenson, 1992) casts doubt on

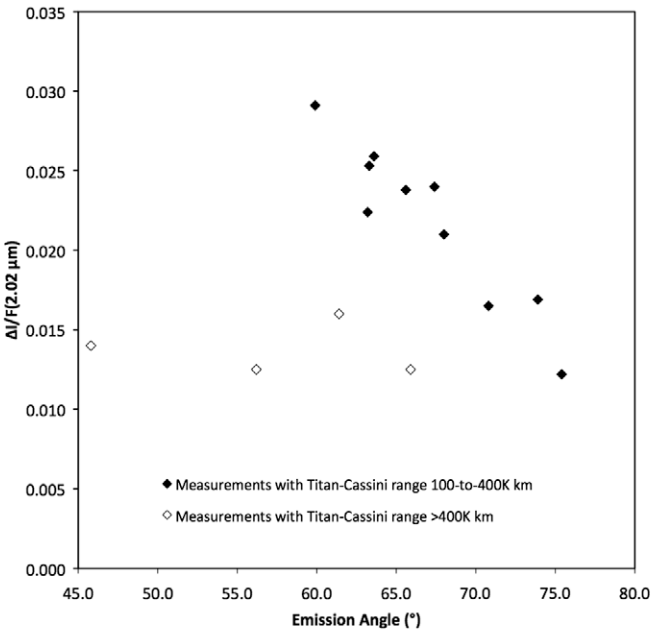


**Fig. 5.** VIMS data from Nelson et al. (2009). If low-resolution data (Cassini-Titan range $>4 \times 10^5$ km) are excluded, the data show a strong and simple correlation between falling contrast and increasing emission angle. This is a natural consequence of aerosol scattering; no excursions in brightness or reflectance of Hotei Regio are required to explain the observations.

the idea that the effluent responsible for an apparent brightness changes is pure ammonia. Rather this material would more likely be in the form of ammonia hydrate, whose reflectance spectrum is only marginally different than that of water ice (cf. Brown et al., 1988). Also most of the VIMS observations analyzed by Nelson and colleagues were made when Hotei Regio was quite close to Titan's limb, resulting in large emission angles (most > 60°) and large optical path-lengths, making their simple approach to extraction of surface reflectance variation (by differencing the brightness with that of the surrounding region) dubious, particularly for wavelengths <3 µm. In Fig. 5 we re-plot the emission-angle dependence (data originally shown as part of Fig. 5 of Nelson et al. (2009)). We have used their published data (emission angle and spacecraft range from Table 1 of Nelson et al. (2009) and $\Delta I/F$ relative to surrounding "photometric control points" provided in Table 2 of Nelson et al. (2009)). Fig. 5 shows that if one excludes measurements with lower resolution (for which the Cassini-Titan range was >400,000 km and VIMS resolution >200 km/pixel) a strong and simple correlation between a drop in contrast ($\Delta I/F$) and increasing emission angle is revealed. This is the behavior one would expect for Titan's aerosol-ladened, multiply scattering atmosphere. The low resolution of the remaining data points, collected from ranges >400,000 km (open diamonds), accounts for dilution of contrast and for their falling below the trend. For example, one point from T12 with an emission angle of 45.8° in Fig. 5 was acquired at a range of 810,000 km and has a limb-ward VIMS resolution projected to the surface >550 km/pixel. In summary, although the evidence we have described suggests geologically recent volcanic activity at Hotei Regio, we conclude that the VIMS observations to date do not provide compelling evidence for Cassini actually having witnessed ongoing volcanic activity in Hotei Regio.

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