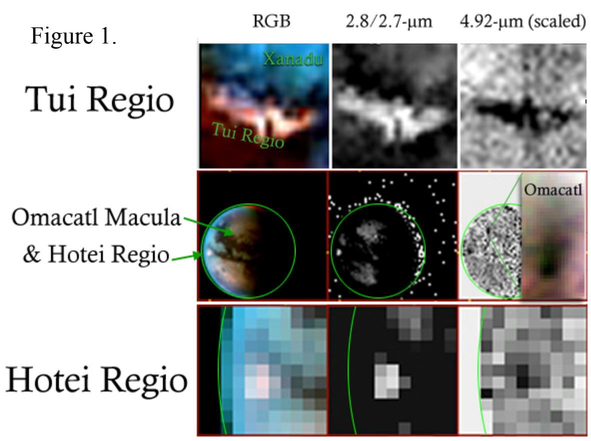
TITAN: OBSERVATIONAL CONSTRAINTS ON CRYOVOLCANISM. P. Hayne[1,2], T. B. McCord[2], J-Ph. Combe[2], J. W. Barnes[3], G. B. Hansen[2,4]. [1]University of California, Los Angeles (595 Charles Young Blvd E, Los Angeles, CA 90095; phayne@ucla.edu), [2]The Bear Fight Center (PO Box 667, Winthrop, WA 98862), [3]NASA-Ames Research Center (Moffett Field, CA), [4]University of Washington (Seattle, WA).

Introduction: We have identified three anomalous features on Titan's surface, which we hypothesize are recently active cryovolcanic constructs. This hypothesis is evaluated in the context of previous analyses of data from the Cassini mission, as well as geophysical models of magmatism on icy satellites. Previous observations by the Visual and Infrared Mapping Spectrometer (VIMS) indicate that CO_2 ice is likely present (in addition to water ice), while ammonium sulfates are not a dominant component. Methane clathrate hydrate, which is expected to be present at or near Titan's surface, cannot be verified or ruled out based on the VIMS data alone, due to atmospheric effects at key wavelengths. The composition and morphology of apparent cryovolcanic features can be used to constrain the physical and chemical environment, as well as the interior structure and evolution of Titan.

Figure 1.



Regions of Interest: Two ~100-km bright spots on Titan's surface, Tui Regio and Hotei Regio, are characterized by their unusually high reflectance at 5 μm wavelength, and were previously suggested as possible volcanic sources [1]. A third location shows remarkably similar spectral (and likely compositional) characteristics, and is just adjacent to the unique dark spot Omacatl Macula – a possible source of dark dune material [2] (Fig 1). All three regions lie within 30° of the equator, on bright terrain near the margin with equatorial dark material. In addition to the presence of apparent lobate flow features [1], Hotei and Tui Regio may each be associated with regions of fluctuating brightness [3], further implicating them as active centers of volcanism. Figure 1 illustrates the primary spectral attributes of the three surface anomalies. (For the left panel, R=5.0, G=2.0, B=1.6 μm.)

Presence of CO_2: A previous publication described three lines of spectral evidence suggesting the presence of CO_2 frost on most of Titan's surface, especially concentrated in the three regions of interest [4]:

(1) Overall spectral shape. Linear spectral unmixing of the VIMS data indicates that the majority of Titan's surface can be modeled well by a combination of carbon dioxide frost (of 10–100 μm grain size), water ice, and an unknown component bright at 2 μm.

(2) 2.7-μm slope. One of the most salient spectral features of Tui Regio, Hotei Regio, and the Omacatl anomaly, is their anomalously high 2.8/2.7-μm reflectance ratio – a trait again shared with CO_2 ice of small grain size (cf. center panel of Fig. 1 and Fig. 2).

(3) 4.9-μm absorption. The only convincing molecular absorption feature so far detected by VIMS on Titan's surface occurs near 4.9 μm, and is attributed to CO_2 frost of small (10–100 μm radius) particle size, complexed with other solids, likely H_2O ice.

Figure 2 compares the Tui Regio VIMS spectrum to that of several candidate materials for Titan's surface. While CO_2 with some amount of H_2O provides a good match, the inverted spectral slope between 2.7 and 2.8 μm is not consistent with fine-grained ammonium sulfate. This is significant, since some Titan interior models predict the production of ammonium sulfate minerals from the reaction of aqueous $MgSO_4$ with ammonia in Titan's putative internal ocean [5].

Stability of $CO_2(s)$: In addition to our surface observations, CO_2 has been detected in Titan's upper atmosphere by CIRS with a mixing ratio orders of magnitude higher than the saturation ratio at the tropopausal cold trap [6]. At the 1.5-bar pressure of Titan's surface, CO_2 is in the solid phase, with an equilibrium vapor pressure (assuming T≈85–95 K) $p_s \approx 10^{-10}$–10^{-8} bar [ref. 7]. We therefore reasonably expect that the lower atmosphere is saturated by the gaseous phase (though it should nonetheless be below the detection threshold of the Huygens GCMS; ref. 8), and the solid CO_2 phase is stable to sublimation on the surface.

Due to its higher density ($\rho_{CO2} \approx 1560$ kg·m^{-3}) than both pure water ice ($\rho_{H2O} \approx 970$ kg·m^{-3}) and various methane and ammonia hydrate shells ($\rho_s \approx 900$–1100, ref. 5), a layer of pure CO_2 solid overlying an icy layer of either composition will be gravitationally unstable. Consistent with the spectroscopic evidence [4], this

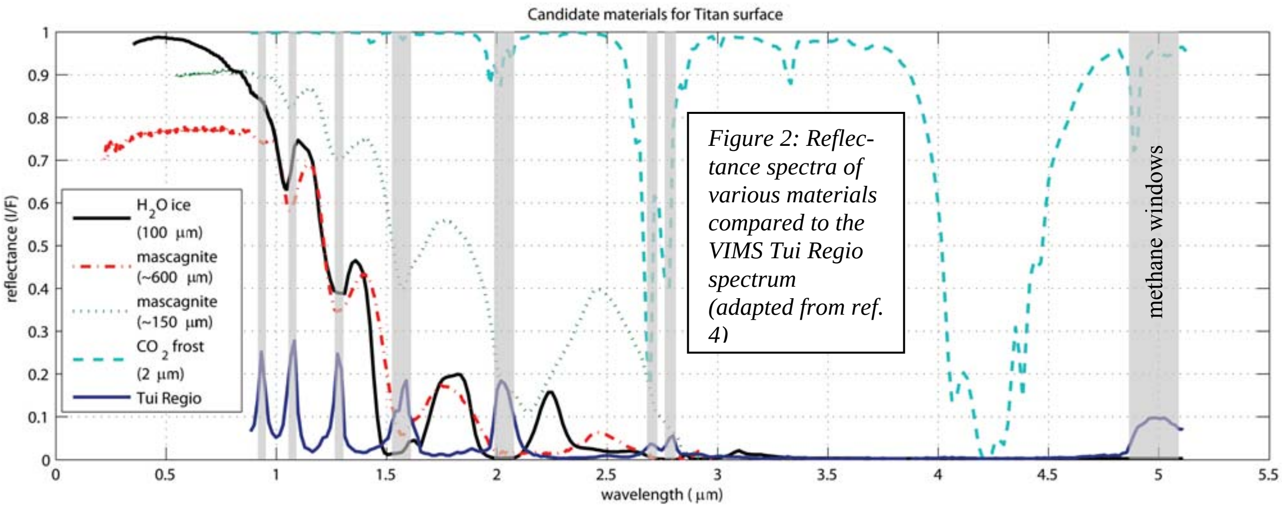


Figure 2: Reflectance spectra of various materials compared to the VIMS Tui Regio spectrum (adapted from ref. 4)

inherent instability suggests the CO_2 (though widespread) is neither pure nor present in large quantities relative to lower density crustal materials.

Role of CO_2 in Cryovolcanism: A previous article suggested that carbon dioxide is a major constituent of Titan's near surface layers, particularly in areas of recent activity [4]. However, spectroscopic and geophysical evidence supports a model in which CO_2 is not the primary component of Titan's cryomagma; its large positive $\Delta\rho$ compared to reasonable ice shell compositions likely precludes it as a buoyancy-driven extrusive melt. Rather, we propose a scenario in which CO_2 is a solid-phase component of the bulk ice shell (typically modeled as ~30 km thick, for a NH_3–H_2O ocean composition; ref. 9), which is primarily Ice Ih overlain by CH_4 clathrate hydrate. Eruptions of methane clathrate (and/or ammonia-water) could preferentially occur within crustal material rich in CO_2, perhaps due to differences in material strength or rheology. We note evidence exists for heterogeneity in Titan's crustal composition, since certain regions appear to be composed of a substrate richer in water ice than Tui Regio, for instance [4, 10]. Localized high volatile content due to cometary impacts cannot be ruled out.

The simultaneous presence of NH_3 and CO_2 is possible, depending on the quantity of CO_2 available in the ocean to sequester aqueous ammonia as carbonate [11, 12]. Titan's atmospheric methane absorption could conceal the composition of other constituents of the cryolava, including ammonia and hydrocarbons. As discussed previously however, we find that in the case of ammonium sulfate (mascagnite), the VIMS spectra of the 5-μm-bright regions are better matched by CO_2.

Summary and Future Work: Multiple episodic eruptions of CO_2-containing cryolava from a zone of crustal weakness best explain the morphology and composition of Tui Regio, Hotei Regio, and a similar region near Omacatl Macula. Cryovolcanic terrain (expressed as 5-μm-bright material) near Omacatl Macula (one of the darkest features on Titan, and a likely source of dark dune material; ref. 2) could be coincidental, but is more likely due to regional tectonism. Similarly, the coincidence of the two most prominent 5-μm-bright spots (Tui and Hotei Regio) at approximately the same latitude as Omacatl but in the southern hemisphere (near the edge of Xanadu), is probably an expression of a symmetric global stress pattern. Both Tui and Hotei Regio are associated with 2-μm-bright arcuate features prominent in ISS images, which could be cracks or source vents. Their geometry may be indicative of changes in tensile stresses in the crust.

Future work will further address the geophysical consequences of the observations presented here. For instance, based on the morphology of flow features mapped by [1], the style of volcanism on Titan appears to be effusive. Continued analysis of the VIMS dataset, combined with modeling efforts similar to those of Lorenz (1996; ref. 13) including CO_2 and potentially other volatiles, should begin to reveal a clearer picture of cryovolcanism on Titan.

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