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

Presence of CO\textsubscript{2}: A previous publication described three lines of spectral evidence suggesting the presence of CO\textsubscript{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 \(\mu\)m grain size), water ice, and an unknown component bright at 2 \(\mu\)m.

2. 2.7-\(\mu\)m 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-\(\mu\)m reflectance ratio – a trait again shared with CO\textsubscript{2} ice of small grain size (cf. center panel of Fig. 1 and Fig. 2).

3. 4.9-\(\mu\)m absorption. The only convincing molecular absorption feature so far detected by VIMS on Titan’s surface occurs near 4.9 \(\mu\)m, and is attributed to CO\textsubscript{2} frost of small (10–100 \(\mu\)m radius) particle size, complexed with other solids, likely H\textsubscript{2}O ice.

Figure 2 compares the Tui Regio VIMS spectrum to that of several candidate materials for Titan’s surface. While CO\textsubscript{2} with some amount of H\textsubscript{2}O provides a good match, the inverted spectral slope between 2.7 and 2.8 \(\mu\)m is not consistent with fine-grained ammonium sulfate. This is significant, since some Titan interior models predict the production of ammonium fluoride minerals from the reaction of aqueous MgSO\textsubscript{4} with ammonia in Titan’s putative internal ocean [5].

Stability of CO\textsubscript{2}(s): In addition to our surface observations, CO\textsubscript{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 tropopause cold trap [6]. At the 1.5-bar pressure of Titan’s surface, CO\textsubscript{2} is in the solid phase, with an equilibrium vapor pressure (assuming T=85–95 K) \(p_s\approx10^{-10}\)–\(10^{-8}\) 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\textsubscript{2} phase is stable to sublimation on the surface.

Due to its higher density (\(\rho_{CO_2}\approx1560\text{ kg m}^{-3}\)) than both pure water ice (\(\rho_{H_2O}\approx970\text{ kg m}^{-3}\)) and various methane and ammonia hydrate shells (\(\rho_s\approx900–1100\), ref. 5), a layer of pure CO\textsubscript{2} solid overlying an icy layer of either composition will be gravitationally unstable. Consistent with the spectroscopic evidence [4], this
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 geological 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$_2$O 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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