

CRYOVOLCANISM AND METHANE OUTGASSING ON TITAN. G. Mitri¹, A. P. Showman², J. I. Lunine², and R. M. Lopes¹, ¹Jet Propulsion Laboratory, California Institute of Technology (4800 Oak Grove Dr. Pasadena California, Giuseppe.Mitri@jpl.nasa.gov), ²Lunar and Planetary Laboratory, University of Arizona (1629 E. University Blvd. Tucson Arizona).

Introduction: Cassini Radar has observed flow-like features interpreted as cryovolcanic in origin [1]. Also other icy moons of Jupiter, Saturn and Uranus show candidate cryovolcanic features. Several mechanisms have been proposed for cryovolcanic eruptions on icy satellites: gas exsolution following depressurization in fluid-filled fractures that propagate upward from the base of the ice shell [2]; explosive eruptions of sprays [3]; pressurization of liquid chambers in an ice-I shell [4,5]; and cryomagma transport to the surface through cracks in an ice-I shell [6]. Showman et al. [5] proposed for Ganymede that tidal heating partially melts the shallow ice shell (between 5 km and 10 km from the surface). They have shown that surface topography (for example graben) produce pressure gradients within the ice shell that might pump water from the interior of the ice shell to the surface. Fortes et al. [7] proposed a resurfacing model on Titan based on the assumption that large amounts of sulfur leached into the internal ocean; we do not pursue this model further because the leaching has yet to be quantitatively calculated, and radiometric data from Cassini [8] are not consistent with large amounts of ammonium-sulfate compounds on the surface.

Cryovolcanism could be related to the presence of ammonia-water in Titan's interior [1,6,9]. To date, models of ammonia-water resurfacing have not been tied to specific events or evolutionary stages within Titan's interior. Here we will test the hypothesis that ammonia-water can promote resurfacing and we will propose a model of cryovolcanism involving ammonia-water magma on Titan.

Resurfacing by ammonia-water cryomagma: Evolutionary models support (but do not require) the presence of an ammonia-water subsurface ocean on Titan [e.g.,10]. Much of the impetus for invoking ammonia as a constituent in an internal ocean comes from the negative buoyancy of pure liquid water with respect to pure water ice, which prevents eruption from the subsurface ocean to the surface. However, the peritectic ammonia-water liquid with a composition near that of pure ammonia dehydrate ($\text{NH}_3 \cdot 2\text{H}_2\text{O}$) has a density (946 kg m^{-3}), which is close to neutral buoyancy with respect to the water ice (920 kg m^{-3}). A marginally negatively buoyant mixture might allow effusive eruptions from a subsurface ocean [9]. If the subsurface ocean were cool enough to become a neu-

tral buoyancy mixture, all the ammonia would have been erupted very early in Titan's history. Either the surface would be full of ancient cryovolcanic features, or erosion would have erased all of these. Contrary to this scenario, Cassini-Huygens has so far observed neither a global abundance nor a complete dearth of cryovolcanic features. Further, an ancient cryovolcanic epoch cannot explain the relative youth of Titan's surface (0.2 – 1 Gyr [11]).

Crucial to invoking ammonia-water resurfacing as the source of the apparently recent geological activity is not how to make ammonia-water volcanism work (because the near neutral buoyancy of the ammonia-water mixture offers an easy explanation), but rather how to prevent eruption from occurring so easily that cryovolcanic activity is over early on.

If the ice-I shell contains liquid ammonia-water pockets that partially freeze, then the ammonia concentration can approach the eutectic within these pockets. Freezing of ammonia-water pockets in the ice shell might promote positive buoyancy of the liquid trapped into the ice shell even when the ocean itself is not buoyant. While the liquid density in these pockets cannot easily become buoyant relative to the surrounding ice, we argue that these concentrated ammonia-water pockets are sufficiently close to neutrally buoyant that large-scale tectonic stress patterns would enable the ammonia to erupt effusively onto the surface, at least episodically. Stresses associated with tides, nonsynchronous rotation, satellite volume changes, and solid-state convection in the ice may all promote an environment where near-neutrally buoyant ammonia-water residing in subsurface pockets can be delivered effusively onto the surface at localized times and places. Even stress gradients associated with topography could contribute, as has been suggested for Ganymede [5]. Thus, the process of partial freezing of ammonia-water pockets trapped in the ice shell provides a possible mechanism for explaining intermittent cryovolcanism on Titan. Because of the relative inefficiency of trapping liquid in the shell and transporting it to the surface, this scenario can explain why Titan did not lose all its ammonia into cryovolcanic flows early in Solar System history; likewise it explains why Titan's surface is not covered with cryovolcanic flows now. Because we posit that the cryovolcanic liquid comes from localized pockets rather than

directly from the ocean, our scenario also allows the ocean to remain dilute in ammonia, hence much denser than the overlying ice and mechanically stable over Solar System history.

Crevasses in the bottom of the ice-I shell can trap oceanic masses, forming ammonia-water pockets. We follow the terminology used in glaciology and we call the cracks at the base of the ice-I shell bottom crevasses. The bottom crevasses have a high penetration depth in the sheet because ocean water fills the cracks, and therefore the pressure of the water on the crevasse walls counters the hydrostatic pressure of the ice that tends to close the fractures. Refrozen bottom crevasses are common features in terrestrial ice sheets. In a freezing crevasse the ice grows laterally into the crack and cannot trap liquid in the ice during its crystallization. On other hand, the trapped oceanic water in an open crack during the tidal flexing of the ice shell is almost all expelled before a new tidal cycle occurs. To trap liquids in the ice, the base of the ice shell must be under compression and at the same time the middle part of the crack must be unstressed or under extension. A suitable process is the rapid refreezing of the ice shell base such that the interior of a deep crack does not itself become frozen. Convection can aid this process by allowing rapid changes in ice thickness. A faster and larger variation in thickness of the ice shell is expected if the onset of convection occurs in the ice [10]. In this case changes in the thickness of the ice shell of several tens of kilometers in a timescale of $1\text{--}5 \cdot 10^6$ yr are expected.

Methane outgassing: Exsolution of soluble gases near the surface would also promote eruption of liquid onto the surface. Methane clathrates are stable in the ice shell in the absence of destabilizing thermal perturbations and/or pressure variations. The presence of ammonia in a water solution changes the methane clathrate stability curve. We find that methane clathrate present in liquid pockets with a high ammonia mass concentration can dissociate in Titan's ice shell. Fig. 1 shows the methane clathrate curve stability for four ammonia mass concentration (0%, 15%, 30%, and 45%). The dashed lines show a plausible range of the cryomagma temperature (177 K - 239 K). For example, for ammonia mass concentrations of 15% destabilization of clathrate occurs close to the surface. On other hand, for ammonia mass concentration of 30% the clathrate present in ammonia-water pockets is not stable at all. One can thus imagine a scenario where ammonia-water pockets with methane clathrate are transported from the base of the ice shell to the base of the stagnant lid. The refreezing of the pockets produce an increase of the ammonia concentration and

therefore the clathrate can dissociate. Exsolution of methane in the pockets can produce overpressure and consequently the ammonia-water can erupt to the surface leading to cryovolcanism. Methane outgassing during cryovolcanic events can resupply the methane abundance in the atmosphere.

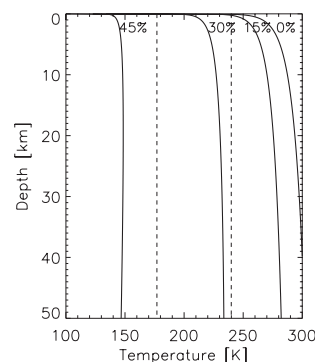


Figure 1. Methane clathrate curve stability for four ammonia concentrations (by mass) (0%, 15%, 30%, and 45%). The dashed lines show a plausible range of the cryomagma temperature (177 K - 239 K).

Conclusions: We have shown that cryovolcanism by ammonia-water magma can occur on Titan. Our model of cryovolcanism involves cracks and formation of ammonia-water pockets in the ice-I shell. We have shown that ammonia-water trapped in the ice-I can be buoyant and thus allow effusive eruptions. Based on evolutionary models we favor a scenario where cryovolcanic features could have been associated with relatively recent geological activity and episodes of methane outgassing. The onset of convection in the ice-I shell can play an important role in ensuring recent cryovolcanism activity on Titan.

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