ERUPTION OF AMMONIA-WATER CRYOMAGMAS ON TITAN 2: ERUPTION STYLES AND LANDFORMS.

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Introduction: We are developing models for the ascent and eruption of cryomagmas on Titan, based largely upon previous silicate magmatic conduit flow models and modified for assumed ammonia-water chemistry. Preliminary results based on thermodynamic analysis are presented elsewhere [1]. Here we present an analysis of likely eruption styles resulting from a range of input conditions, and compare these with current observations of likely cryovolcanic features on Titan. Several candidate volcanic features from Ta observations are discussed.

Explosive eruptions: To date, no explosive features have been interpreted on the surface of Titan based on remotely sensed data. On the Earth, explosive volcanism tends to occur when the erupting mixture is dominated by gaseous volumes, typically when the volume fraction of gas exceeds ~74% [2]. We assume an ammonia hydrate magma with a density of 950 kg m^{-3}, containing methane modelled as an ideal gas. Under Titan's 1.5 bar atmospheric pressure, a minimum of 0.35 wt% methane is required to produce magma fragmentation, given 176 K eruption temperature and a lithostatically pressure-balanced conduit. This figure will decrease down to a possible 0.25 wt% if temperatures are significantly elevated. Such mass fractions are similar to those of CO_2 in mild basaltic Hawaiian fire-fountaining episodes. However, it is necessary for the gas to remain dynamically well-coupled with the ascending magma. On the Earth, magmas with several times the mass fraction required to produce fragmentation can produce non-explosive activity if magma and volatiles become decoupled [3], which is likely if bubbles coalesce due to slow ascent and/or inclined conduits, or if supersaturation or conduit overpressure occurs. This possibility is enhanced at low viscosities, often resulting in effusive or Strombolian styles of activity. Given the low viscosities of ammonia hydrates, we consider such phase separation to be highly likely. Unfortunately, a thorough analysis of methane solubility in ammonia hydrates is not available, but early indications are that it is low [4], at least compared with that in pure water, which may limit the availability of methane for fueling magma ascent and erupton.

Effusive eruptions feeding lava flows: Although several candidate lava flows were observed in the Ta SAR scene, our ability to model these is limited by the lack of availability of high resolution topography. Kirk et al. [5] presented a preliminary analysis of one of these flows, consisting of two sequential lobes each ~40 km in length, emanating from a bright-rimmed circular feature (41ºW, 47ºN) interpreted as a caldera. It exhibits an unusually bright near-edge and dark far-edge across the flow, over its entire observed length, and appears to be relatively photometrically uniform, so is a candidate for morphometric analysis using a prototype radarclinometric method. Preliminary findings for one transect suggests a thickness of ~200–300 m, with maximum cross-flow slopes of ~7º [5,6]. Using a simple Bingham plastic flow model [6], these slopes suggest a yield strength of ~10^4 Pa, which is comparable to that of basaltic andesites on the Earth.

If the flow morphology were controlled primarily by bulk rheological characteristics in a similar manner to terrestrial silicate magmas, it would have probably exhibited a high effective bulk viscosity (>>10^4 Pa s, inferred from past terrestrial studies, e.g. [7]). However, in liquid form, ammonia-water cryomagmas exhibit weaker and less viscous properties than terrestrial silicates [8]. We propose three possible explanations for this apparent inconsistency: (1) the flow has a predominantly solid fraction (from [9]), as a result of cooling during ascent (unlikely at emplacement in the light of our conduit ascent analysis [1]), ingestion of lithics, and cooling during surface flow (note that proximal levees appear similarly thick to distal ones); (2) solid (ice) and liquid phase separation, resulting in the formation of a strong crust; (3) more viscous chemistry than modeled, such as the addition of methanol [8]; or (4) eruption into a standing body of methane, resulting in pillow formation [10], which seems unlikely due to the apparent regional gradient inferred from flow directions [6].

Other flows observed in Ta are not so well suited to radarclinometry, due to apparent photometric variability. However, our qualitative assessment suggests that most others have less pronounced levees.

Dome forming eruptions: Volcanic domes form when eruption rates are low, probably due to partial solidification in the conduit of rising magmas leading to increased viscosity and yield strength. Their behaviour depends on the eruption rate, magma rheology and thickness of the cooling surface or crust (Fink and Griffiths, 1998). A dome's morphological characteristics can be related to the physical and flow properties using the following relationship:

$$\Psi_B = t_S / t_A = (g \, \Delta\rho / \sigma)^3 \, Q \, t_S \qquad (1),$$

where Ψ_B is the dimensionless ratio of the time necessary for fresh magma exposed at the surface to reach its solidification temperature, t_S, and, the time needed for the viscous flow to advance a distance equal to its thickness, t_A. Also, g is the acceleration due to gravity, $\Delta\rho$ is the density contrast between the flow and its environment, σ is the dome bulk strength and Q is the eruption rate [12]. Analysis of the equation suggests that, for given eruption properties, Ψ_B should be less on Titan than on the Earth by greater than an order of magnitude. However, ammonia-water cryomagma strengths are also likely to be considerably less than those of silicate magmas, as inferred from their lower viscosities, offsetting much of this difference.

Ganesa Macula. One feature, an ~180-km circular rise of unknown height detected by the Radar in SAR mode [13] named Ganesa Macula (fig. 1), has a morphology remniscent of "low" [14] or "axisymmetric" [11] silicate domes, although a shield volcano analogue has also been suggested [6]. If the dome interpretationn is accepted, then this is suggestive of relatively low yield strengths and/or high effusion rates ($\Psi_B > 15$). Note that domes of this areal extent have never been observed elsewhere. The SE flanks of Ganesa exhibit a higher density of fractures and flows than elsewhere. This is roughly the same orientation as the direction of other flows in the rest of the Ta SAR scene, suggesting that the pre-existing surface exerted some control on their orientation. The morphology of putative flows emanating from the south and east sides of Ganesa is not indicative of viscous flows: they are instead thin, sheet-like and broad. This, we suggest, is the result of eruption of crystal-depleted cryomagmas following partial or complete solid and liquid phase separation. An attractive analogy would be that of a "snow cone" or some other partially-frozen slurry drink containing insufficient emulsifier to completely bind the syrup to the ice crystals. The liquid component is overpressured due to a hydraulic head, and will tend to be driven gravitationally through the interconnected pore spaces. Sector collapse may also play a role, particularly in initializing the larger flows.

Discussion: A broad range of probable cryovolcanic features have been discovered on Titan, by Radar and near-IR mapping from Cassini, and understarting their complex formation histories will be difficult. The very preliminary analyses presented here suggests that crystallization and phase separation, and the processes that affect them, are likely to be critical in understanding the morphological differences between landforms. Further advances will be made possible by the acquisition of topographic data on the imaged landforms, as well as rheological and chemical lab measurements of candidate cryovolcanic materials.

References: [1] Mitchell K.L. et al. (2006a) *LPS XXXVII*, Abstract #2355. [2] Sparks R.S.J. (1978) *JVGR, 3*, 1-37. [3] Mitchell K.L. et al. (2002) *LPS XXXIII*, Abstract #1766. [4] Grasset O. & Pargamin J. (2005) *Planet. Space Sci., 53*, 371-384. [5] Kirk R.L. et al. (2005) *LPS XXXVI*, Abstract #XXXX. [6] Lopes R.M.C. (in review) *Icarus*. [7] Pinkerton H. & Wilson L. (1994) *Bull. Volcanol., 56*, 108-120. [8] Kargel J.S. et al. (1991) *Icarus, 89*, 93-112. [9] Petford N. (2005) *LPS XXXVI*, Abstract #1043. [10] Lorenz R.D. (1996) *Planet. Space Sci., 44*, 1021-1028. [11] Fink J.H. & Griffiths R.W. (1998) *JGR, 103*, 527-545. [12] Griffiths R.W. & Fink J.H. (1997) *JFM, 347*, 13-36. [13] Elachi C. et al. (2005) *Science, 308*, 970-974. [14] Blake S. (1990) *in IAVCEI Proc. Volcan. vol. 2* (ed. J.H. Fink), pp. 88-126. [15] Sotin C. et al. (2005) *Nature, 435*, 786-789.

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Figure 1: Map of the ~180 km diameter Ganesa Macula (GM) and its surrounds, with CTRM SAR Ta scene as a backdrop. Units are defined based on morphological appearance and radar brightness. Note the tendency towards eastward flows (indicated by light arrows).