ERUPTION OF AMMONIA-WATER CRYOMAGMAS ON TITAN 1: CRYSTALLISATION AND COOLING DURING ASCENT.

Introduction: Several cryovolcanic landforms have been interpreted on Titan, indicating a broad range of eruption styles and rheological properties [1,2]. We are developing a semi-analytical model for the ascent of methane-expansion driven ammonia-water cryomagmas on Titan, based upon a silicate magmatic conduit flow model [3]. Some preliminary results are presented based on thermodynamic analysis. The degree of crystallisation of the magma is strongly controlled by the starting depth/pressure. The range of different crystal fractions may help to explain the range of apparent rheological properties inferred for surface features [2].

Thermochemistry: We consider ammonia-water solutions [4] with initial ammonia concentrations <32 wt% (ammonia dihydrate peritectic), consistent with a very water-rich bulk composition dictated by cosmochemical and orbital evolution considerations [6]. The negative buoyancy of most ammonia-water magmas (except dihydrate compositions near the eutectic) may be overcome, as the overpressure for refreezing (10^{7} – 10^{8} Pa) in magma chambers exceeds the lithostatic pressure required to cause a surface eruption by large driving pressures [6]. Crustal density may also be greater than that of pure water-ice, as a result of meteoroid impacts, although this effect may be offset by near-surface fracturing and porosity. However, we consider it likely that magma ascent is driven by the expansion of methane during decompression, because methane is seen in abundance in Titan’s atmosphere, was detected on the surface by the Huygens probe [7] and has appropriate volatility under relevant conditions. Erosolution of methane from the cryomagma is not modelled, due to the lack of a treatment for solubility in, and latent heat of exsolution from, ammonia-water mixtures; we treat only the behaviour of methane after its exsolution. We do not as yet consider the possibility of cryomagmas composed of sulphates [8], organics such as methanol (e.g. [9]) or volatiles other than methane such as ethane, as currently-available thermochemical data is insufficient and no increase in model complexity is justified by the data.

The eruptants are considered to be Newtonian and 3-phase: solid water Ice-I (H_{2}O), liquid ammonia hydrates (NH_{3})_{4}(H_{2}O)_{1-3} and gaseous/supercritical methane (CH_{4}). Liquid and solid phases are assumed to be incompressible, and the methane is treated as an ideal gas, which provides a good first order fit over the pressures considered. Mixture viscosity is derived based on empirical data [9], modified to take into account the effect of solid crystals using a method [10] based on the lubrication limit concept of particle interactions. Solid fraction (we assume freezing out of ice forms crystals rather than glasses) is determined using the ammonia-water equation of state ([11] summarized in Fig. 1). Freezing of pure water-ice during decompression and cooling will drive the cryomagma to more ammonia-rich concentrations. If energy is extracted faster than water freezes then it is driven toward the eutectic between ice and ammonia dihydrate, which is shifting to higher ammonia concentrations above peritectic temperatures.

Dynamics: Decompression and ascent of the cryomagma under adiabatic conditions results in temperature and phase changes according to the relation (from conservation of energy, after [3]):

\[ c \, dT = h_{H_{2}O,\text{fusion}} \, \delta m_{i} - (m_{m} / \rho_{m}) \, dP - u \, du - g \, dz \]  

(1),

where \( c \) is the bulk specific heat capacity of the eruptants, \( T \) is the temperature, \( h_{H_{2}O,\text{fusion}} \) is the latent heat of fusion of ice, \( m_{i} \) is the mass fraction in ice, \( m_{m} \) is the mass fraction of the cryomagma (solid + liquid) and \( \rho_{m} \) is its density, \( P \) is the bulk pressure, \( u \) is the ascent velocity, \( g \) is the surface gravity, and \( z \) is the elevation. The physical meaning of the second expression on the right-hand-side of (1) might not be immediately obvious; combined with \( u \, du \) it represents an amalgamation of viscous dissipation and gas expansion.

Analysis: Solution of (1) reveals that adiabatic temperature changes during ascent are generally small.

...magnesia-water ocean [6] represent the deepest plausible near-surface magma chamber. Assuming a pure water-ice crust we consider two end-member scenarios, inspired by [6]: (1) deep eruptions from a magma ocean, (2) shallow eruptions from a shallow reservoir. Either source overpressure or driving volatile expansion is probably necessary for cryovolcanic eruptions. Further theoretical chemistry and/or laboratory work will be necessary to produce a more rigorous analysis of likely styles of cryovolcanic eruptions over a range of compositions.


**Acknowledgements:** This work was supported by the Cassini project, as well as an NRC Research Associateship to KLM carried out at JPL/Caltech.