A SULFATE-RICH MODEL OF TITAN'S INTERIOR 2: IMPLICATIONS FOR POSSIBLE EXPLOSIVE CRYOVOLCANISM.

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Introduction: There has been a great deal of speculation regarding the possibility of cryovolcanic activity of Titan, traditionally involving the extrusion of aqueous ammonia solutions, perhaps from a subsurface ocean [e.g., 1]: Since the Cassini spacecraft arrived in orbit about Saturn, and having made ten Titan flybys to date (out of forty scheduled for the primary mission), it has become apparent that Titan has been (and may still be) cryovolcanically active. Features interpreted as cryovolcanic edifices and flows have been observed in synthetic aperture radar (SAR) data collected during the Ta flyby [2]. Current models predict gentle effusive volcanism, the principle volatile in the magma (methane) being insufficiently soluble in aqueous ammonia to cause explosive activity at Titan's current atmospheric pressure [1]. In a related abstract [3] we present an alternative model of Titan's internal structure and chemistry in which cryomagmatism on Titan involves the extrusion of aqueous ammonium sulfate through a methane clathrate crust. Here we use the model to reassess the role of magmatic volatiles in generating explosive cryovolcanism, and consider the consequences for the state of Titan's surface and atmosphere.

Modelling: In the structural model outlined in Ref. 3, we envisage ammonium sulfate solutions being extruded to the surface either from a subsurface ocean (at a depth of perhaps 150 km), or from melt pockets in the crust itself that were either intruded at the time of crust formation, or were emplaced by solid-state convection in the crust. Eutectic melts in the binary $(NH_4)_2SO_4 - H_2O$ system will have a density of ~1240 kg m^{-3} [4]; therefore, melt extraction through a clathrate crust (mean $\rho = 1000$ kg m^{-3}) is only possible if there is a driving force other than buoyancy, or if the melt can fractionate to a more water-rich (and thus less dense) composition. Possible driving forces include tidal pumping [e.g., 5], or the pressure generated by the volume change upon partial melting. Explosive activity becomes possible if the magma contains a volatile species that is capable of exsolving as it rises towards the surface and decompresses. For Titan, plausible volatile species in the melt include methane, carbon monoxide and nitrogen; here we only consider the role of methane. As a matter of interest, we also note that explosive activity may occur even in the absence of dissolved volatiles, where a magmatic dike intrudes into volatile-laden sediments (such as those observed at the Huygens landing site [6]), or liquid methane seeps down into fractured rocks (ices), coming into contact with magmatic intrusions.

There are two principle methods of introducing methane into the rising cryomagma: i) in solution; and ii) in the form of methane clathrate xenoliths. These form the basis for a range of model scenarios. For liquid sourced in an underground ocean, the methane in solution is that remaining after the extraction of methane to form the crust, and is probably of the order of 0.5 wt % (scenario 1). Melts generated in the crust might in fact contain no dissolved methane at all (scenario 2) unless they are able to equilibrate with methane clathrate country rocks (scenario 3); in this instance the quantity of dissolved methane will be very small (order 0.1 wt % [7]). It is also possible that intracrust partial melts are able to become saturated with methane (~0.5 wt % at 300 bar 270 K, for example [7]); this is scenario 4. In all instances, it is likely that rising magma will incorporate methane hydrate wall rock as xenoliths. These xenoliths play little role (other than providing a minute amount of extra buoyancy) until the clathrate decomposition depth is reached. At an assumed magma temperature of 270 K, this occurs at a pressure of 26 bars [8], or ~2000 metres depth. The decomposition of entrained xenoliths immediately liberates methane gas into the melt over and above that already exsolved (or not) from solution. We consider melts with no dissolved methane and variable xenolith abundances (scenario 5) and methane saturated melts with variable xenolith abundances (scenario 6).

As the magma rises towards the surface, the confining pressure decreases, thus reducing the solubility of methane in the liquid, resulting in exsolution and the nucleation and growth of gas bubbles. If the total gas bubble volume fraction becomes large enough (~60-85%) then the magma is said to fragment, powering a Hawaiian-style explosive eruption [9-11]. If the magma viscosity is higher, bubbles may coalesce, driving strombolian-type activity. In extreme cases, choking of the vent can result in build up of gas-laden foam, or the prevention of gas exsolution. In the first case, sufficient pressure may accumulate to explosively destroy the vent blockage, and in the second case, sudden pressure release may result in violent degassing of the magma, as occurred at Mount St. Helens in 1980, for example.

Experimentally determined values of the solubility of methane gas in water [7,12] are used to determine the mass fraction of methane. Using the basic model described in refs 9 and 10, the exsolved methane mass fraction (n_m) provides the bulk magma density (β), and the bubble volume fraction (V_b);

$$\beta^{-1} = \left[\left(n_m RT\right)/mP\right] + \left[\left(1-n_m\right)/\rho\right] \qquad (1)$$

$$V_b = 1-\beta\left[\left(1-n_m\right)/\rho\right] \qquad (2)$$

where P and T are pressure and temperature, respectively, R is the Gas Constant (8.314 J K^{-1} mol^{-1}), m is the molar mass of the volatile species (methane = 0.016 kg mol^{-1}), and ρ is the density of the bubble-free magma.

For scenarios 4 and 6 we arbitrarily assume that an ammonium sulfate magma originates at a depth of 30 km, which controls the total amount of exsolution that can occur during the ascent. Explosive disruption is considered to occur at the pressure, and hence depth, where the bubble volume fraction reaches either 60% or 75%. The former reflects the likelihood that very low viscosity melts will disrupt more easily, and the latter is for consistency with studies of terrestrial magmas. We then use the fragmentation pressure to determine the velocity of the erupted gas and cryoclastic material through the vent [10], this yielding an estimate of how high may be the resulting lava fountain.

Results: Table 1 summarises the results for each scenario, except scenario 2, where no explosive activity can occur, and scenario 3, where exsolution begins at 2.1 km depth but does not lead to fragmentation. Introduction of clathrate xenolith dramatically increases the explosivity of eruptions – producing ice lava fountains kilometers high, even for xenolith abundances of just a few wt %. For magmas containing no dissolved methane (scenario 5), the critical xenolith content for fragmentation is 1.16 wt % (for $V_b = 0.60$) or 2.33 wt % (for $V_b = 0.75$). Note that magmas in scenario 3 may become explosive at critical xenolith abundances of 0.35 wt % (for $V_b = 0.60$) or 1.40 wt % (for $V_b = 0.75$). Given the very low levels of clathrate entrainment necessary to produce fragmentation, it seems that vigorous explosive cryovolcanism may be the norm rather than the exception on Titan.

Signs of explosive volcanism on Titan: The above model of explosive activity would likely produce an explosion crater (caldera), steep-sided (spatter) cone and an eruption cloud. At present, the most convincing candidate for a cryovolcano is Ganesa Macula, a 180-km diameter feature observed in the Ta SAR swath [2]. This feature has been interpreted by different workers to be dome-like or shield-like; nonetheless it is the apparent source of a series of flow units extending over 100 km to the east. The edifice appears to us to be topped by a caldera-like feature 20 km x 10 km, within which sits a steep cone. The caldera rim is the source of several channels which are mostly (but not exclusively) observed on the eastern and south-eastern flanks. One such channel on the south-eastern flank seems to have drained south-east to form a radar-bright flow unit. In overall size and appearance, we believe that Ganesa quite closely resembles the martian volcano Ceraunius Tholus. It is possible that the channels are the result of dense cryoclastic flows from collapsing explosion columns; these flows have subsequently run-out to the east of the edifice, contributing to a complex pattern of radar-bright flow-like units. The asymmetry in the distribution of the channels may simply reflect a tendency of the eruption columns to collapse in a down-wind direction (assuming generally prograde near-surface winds). The summit caldera and steep cone may then be evidence of explosive collapse and resurgence.

Cryoclastic volcanism could supply large quantities of finely comminuted vesicular ‘ash’ to the surface sediment reservoir. Loose cryotephra deposits may be easily mobilized by liquid methane as substantial ‘mud’ flows, or cryo-lahars. Loosely welded cryotephra will probably be more erodible than polycrystalline ice; in addition to airfall deposits, the conclusion must be that cryoclastic volcanism results in Titan’s surface bearing more sedimentary material than it might do otherwise, a factor perhaps in forming the widespread dune fields observed in SAR imagery. Given the large density difference between ammonium sulfate and water ice, we would expect ice to be more easily mobilized by wind and liquid methane, leaving ammonium sulfate grains as a ‘lag’ deposit.

Discussion: For reasonable global magma extrusion rates of $0.5 – 1.0 \times 10^{12}$ kg yr^{-1}, the photolytic destruction of atmospheric methane may *just* be buffered if the magma is saturated with methane in the source region (i.e., the magma contains 0.5 wt % CH_4). If the magma contains a more realistic 0.1 wt % CH_4, then it is necessary to entrain and decompose roughly 3 – 8 wt % of methane clathrate xenoliths: such values of xenolith abundance (which are perfectly reasonable xenolith abundances in terrestrial magmas) will lead to vigorously explosive volcanic eruptions.

Unambiguously cryovolcanic features might yet be observed in Cassini SAR imagery. However, a future mission to Titan will be needed to characterise these features in adequate detail, investigating the small-scale morphology of flow units (particularly possible small ash cones and spatter deposits), as well as the mineralogy, grain size and vesicle size of cryovolcanic deposits. The latter will require the capacity to image samples on microscopic scales, and possibly the ability to make in situ x-ray diffraction measurements.

References: [1] Lorenz, R.D. (1996) *Planet. Space Sci.* **44**, 1021-1028. [2] Elachi, C. *et al*. (2005), *Science* **308**, 970-974. [3] Fortes, A.D. & Grindrod, P.M. (2006) *LPSC* **37**, # 1293. [4] Tutton, A.E.H. (1903) *J. Chem. Soc. Trans*. **1903**, 1049-1074. [5] Mitri, G., *et al.,* (2005) [6] Niemann, H.B. *et al.,* (2005) *Nature* **438**, 779-784. [7] Handa, Y.P. (1990*) J. Phys. Chem*. **94**, 2652-2657. [8] Miller, S.L. (1985) *Ices in the Solar System*, 59-79. [9] Pinkerton, H. *et al.* (2002) *Contemp. Phys.* **43**, 197-210. [10] Head, J.W. & Wilson, L. (2003) *J. Volcanol. Geoth. Res.* **121**, 151-193. [11] Parfitt, E. (2004) *J. Volcanol. Geoth. Res.* **134**, 77-107. [12] Lekvam, K., and Bishnoi, P.R. (1997) *Fluid Phase Equilibria* **131**, 297-309.

Table 1. Summary of results for those scenarios leading to fragmentation.

	For fragmentation at $V_b = 0.60$			For fragmentation at $V_b = 0.75$		
Scenario	Fragmentation depth (m)	Eruption velocity (m s^{-1})	Lava fountain height (m)	Fragmentation depth (m)	Eruption velocity (m s^{-1})	Lava fountain height (m)
1	260	39.8	585	80	26.5	259
4	300	44.1	717	100	30.8	350
5*	920	90.2	3004	410	75.3	2095
6*	1310	114.6	4853	610	98.7	3600

*For the particular case of 10 wt % methane clathrate xenoliths