CRYOVOLCANISM ON TITAN. K. L. Mitchell and R. M. C. Lopes, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA 91109-8099. (Karl.L.Mitchell@jpl.nasa.gov).

Abstract: In the context of ocean worlds, cryovolcanism is a process in which heat is released from an icy world's interior by mass transit and eruption of a materials sourced primarily from the ocean, via a conduit or opening [1]. Cryovolcanism has been widely conjectured in some form on Saturn's moon, Titan, since the 1970s [2]. A strong argument in favour of recent activity is the make-up of Titan's thick atmosphere. Methane concentrations, as well as isotope and noble gas concentrations measured by the Huygens GCMS [3], imply geologically recent or on-going outgassing, most likely from a reservoir that contains both methane and argon [4], which is challenging to account for from a single crustal reservoir. It is easiest to explain by mass transport from a subsurface ocean [5], the presence of which has been confirmed by analysis of radio science gravity measurements [6].

However, despite thirteen years of observations, cryovolcanism on Titan remains controversial. Cassini failed to produce definitive evidence, leading to the suggestion that it may not occur at all [7]. Here, we review the evidence in the context of anticipated eruption styles, and discuss challenges in building a case and consensus as to whether or not Titan is a cryovolcanic world.

What should cryovolcanism look like?: Titan's thick atmosphere should suppress explosivity, and in the context of the relatively high viscosity of ammonia-water [8] we might expect morphologies similar to low viscosity basaltic volcanism on Earth, with flows and domes [8, 9]. Getting water to ascend through an icy shell is challenging, and Rayleigh-Taylor-like plumes at the base of the ice shell can be ruled out, which makes hot-spot-like magma chambers and calderas unlikely [10]. Direct ascent through the thick (<100 km [7]) ice shell may occur if the shell can accommodate rapid (brittle) dike propagation [11], in which case eruptions from elongate sources seems likely; In this case we would anticipative massive eruptive volumes, due to direct connection with a widespread reservoir (the ocean) that would not easily depressurize and cause activity to cease.

If indeed cryovolcanism has occurred on Titan, then it may be difficult to identify. Titan's thick obfuscating atmosphere limits determination of surface unit compositions on the basis of spectroscopy, and microwave radiometry suggests that water exposures are relatively rare and primarily associated with relatively fresh impacts. Furthermore, in the context of possible periodic activity [12], cryovolcanic landforms may be buried or otherwise obscured by more active and recent processes: sedimentary, aeolian, hydrological and karstic.

Evidence for cryovolcanism: In the light of these limited data, we propose that, short of direct observation of ongoing activity, the case for cryovolcanism must be made abductively, employing multiple lines of evidence, primarily morphological, enhanced by topography and the relatively crude spectroscopy and photometry when possible. Initial interpretations of cryovolcanic landforms on the basis of inductive comparative morphology [13] have been rejected thanks to improved (mostly topographic) data [7, 14]. Polar lake basins, interpreted as calderas or maars with eruptive positive relief annuli [15], would require an unusual geophysical context, and in the polar context we prefer a karstic interpretation [16]. Some landforms such as Hotei Regio [14] are harder to dismiss, but are rare and their morphologies are inconsistent. Of these, the Sotra region [14] is arguably the strongest candidate, including a massive pit (Sotra Patera), flow-like features (Mohini Fluctus), and unusually high mountains (Doom and Erebor Montes). However, as well as being unique, the deep pit is difficult to rationalize with the discussed buoyancy issues and probable lack of caldera-forming processes.

Conclusion: Interpretation of Cassini data has been insufficient to demonstrate conclusively whether Titan is, or ever has been, cryovolcanically active. We propose that a new mission will probably be required to resolve the controversy.

References: [1] Lopes, R.M.C. et al. (2010) *Geol. Soc. Am. Spec. Paper* 470, 11-30; [2] Lewis, J. S. (1972) *Icarus* 16, 241-252; Croft, S. K. et al. (1988) *Icarus* 73, 279-293; [3] Niemann, H. B. et al. (2005) *Nature* 438, 779-784; [4] Tobie, G. et al. (2009) *PTRS-A* 367, 617-631; [5] Stevenson, D. J. (1992) in Proc. Symp. Titan, pp. 2933; [6] Iess, L. et al. (2012) *Science* 337, 457-459; [7] Moore, J. M. and Pappalardo, R. T. (2011) *Icarus* 212, 790-806; [8] Kargel, J. S. et al. (1991) *Icarus* 100, 556-574; [9] Lorenz, R. D. (1996) *Planet. Space Sci.* 44, 1021-1028; [10] Head, J. W. and Wilson, L. (1992) *JGR* 97, 3877-3903; [11] Mitri et al. (2008) *Icarus* 196, 216-224; [12] Tobie G. et al. (2006) *Nature* 440, 61-64; [13] Sotin, C. et al. (2005) *Nature* 435, 786-789; Elachi, C. et al. (2005) *Science* 308, 970-974; Lopes, R. M. C. et al. (2007) *Icarus* 186, 395-412; [14] Lopes R. M. C. et al. (2013) *JGR* 118, 416-435; [15] Wood, C. A. et al. (2007) *LPS XXXVIII*, Abstract #1454; [16] Mitchell, K. L. et al. (2008) LPS *XXXIX*, Abstract #2170.

Acknowledgments: This research was carried out at JPL Caltech under a contract with NASA. We thank the Cassini RADAR team for support and discussions.