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THE FORMATION OF HIGH LATITUDE KARST LAKES ON TITAN AND IMPLICATIONS FOR THE EXISTENCE OF POLAR CAPS. K. L. Mitchell¹ (*Karl.L.Mitchell@jpl.nasa.gov*), R. M. C. Lopes¹, J. Radebaugh², R. D. Lorenz³, E. R. Stofan⁴, S. D. Wall¹, J. S. Kargel⁵, R. L. Kirk⁶, J. I. Lunine⁷, S. J. Ostro¹, T. G. Farr¹ and the Cassini RADAR Team, ¹Jet Propulsion Laboratory, Mail Stop 183-601, 4800 Oak Grove Dr., Pasadena, CA 91109-8099, USA, ²Brigham Young University, Dept. of Geological Sciences, ³Applied Physics Laboratory, Johns Hopkins Univ., ⁴Proxemy Research Inc., ⁵Univ. Arizona, Dept. of Hydrology & Water Resources, ⁶USGS Flagstaff, ⁷Univ. Arizona, Lunar & Planetary Lab..

Introduction: Titan's north polar lakes exhibit variable morphologies, but common to many is that they occupy steep-rimmed depressions, often 100s of metres deep; Kirk et al. [1] measured scarp heights up to 600 m by manual feature-based stereoscopic methods (fig. 1). Lake depressions with this morphology are usually in clusters, and are found to be consistent with karstic or karst-like processes, based on terrestrial analogues and elimination of other possible modes of origin [2] including volcanic and tectonic, on the grounds of distribution, and thermokarst, on the grounds of insufficient insolation.

Karstic processes were not predicted by theoretical modelers, although dissolution as an erosional process was explored by Lorenz & Lunine [3], and should play a critical role in Titan's hydrocarbon cycle. The principal requirement is substantial volumes (a layer of at least 100s of metres thickness) of a solid (solute) that is soluble in the liquids (solvent) and that permits horizontal flow, through pores, fractures or caves. Such a solid cannot be water-ice, the primary constituent of Titan's crust, as this is negligibly soluble in the candidate liquids (methane & ethane) at Titan temperatures ($<10^{-11}$ [3]). The solute's origin is almost certainly through atmospheric photochemical processes (e.g. [4]) and delivered via precipitation, although surface or subsurface processing may be involved. Hydrocarbon production rates (from [4,5,6], summarized in [3]) appear to be sufficient to produce such a massive layer; acetylene production alone could account for a several 100 m thick global layer in 100s of Ma. However, the chemical make-up of this solid layer is debatable, with the main suitable candidate based on atmospheric production rates (acetylene) being prone to reacting in the upper atmosphere to form other materials. Furthermore, it is unclear whether VIMS spectroscopic data of Titan's polar regions will be sufficient to give an unambiguous identification of the material, so we must infer what is possible based on other data.

Model: We present a simple model for karst formation, the goals being to (a) test the plausibility of a simple dissolution model for formation of karst and (b) help to constrain the chemistry of the likely solvent. We assume that the maximum rate of removal of lake floor materials, $dz/dt = A_c r s / (1 - p)$, where A_c is the ratio of the catchment area of the lake (A_{catch}) to the

lake area (A_{lake}), r is the mean rate of methane precipitation, p is the porosity of the solids and s is the solubility by mass of the material in liquid methane at 91 K. Inherent in this treatment are the assumptions that the solvent is saturated and that the rate of evaporation is negligible compared with that of drainage. If either of these assumptions are incorrect, the rate of dissolution will be less. We also assume pure liquid methane is the solvent. It is notable that solubilities of most organics in ethane are two orders of magnitude greater than in methane [7], but Raulin's [8] model suggest polar ethane production rates at several orders of magnitude less than polar methane production rates, and so the role of ethane is likely to be minor.

All of these unknowns in the equations must be assumed, and so there is considerable uncertainty in application of the model. However, use of extreme values may be sufficient for bracketing a suitable range, and therefore hypothesis testing.

For the sake of this exercise, we assume $A_c > 1$, and < 40 , based on preliminary estimates of the ratio of lake depressions (filled or not) to non-lake areas in regions containing many lake depressions. Porosity can only range from 0-1, and will, in the future, be refined further by investigation of snow compaction models and karstic landscapes. For the time being we assume anything greater than 0.5 is unlikely, based on analogues around the solar system. The solubility, s , of various compounds in liquid methane and methane-ethane-nitrogen mixtures under Titan-relevant conditions has been explored by previous workers [3,7,9,10]. We assume a rainfall rate, r , of 0.01 to 2 m a^{-1} , based on Rannou et al.'s [8] polar methane rainfall rate (as high as 1 m a^{-1}), which contrasts considerably with lower latitude rainfall rates (~ 0.01 m a^{-1} [8]). This last unknown is the main source of uncertainty.

Application of the model suggests dissolution rates of $0.01 < 1/s dz/dt < 160$. Given the low number of impact craters on Titan's surface, which implies a surface age of < 1 Ga [11], timescales > 1 Ga seem unlikely. Further constraints on the time of karst formation might be possible based on terrestrial analogue, but we hesitate to do so at present as there are so many unknowns. For instance, are there less dunes in the polar region due to higher rainfall washing them away? In this case the karst is likely to be very young

indeed. Hopefully, further morphological analysis will allow tighter constraints.

However, from this analysis we suggest that solutes with solubilities lower than $\sim 4 \times 10^{-9}$ by mass are implausible. Solubilities in the $\sim 10^{-6}$ to $\sim 10^{-8}$ range may be plausible given ideal conditions, but the time-scales involved will most likely be large. We propose that solubilities of $\sim 10^{-6}$ or greater are more reasonable, which allows us to eliminate a large number of candidate materials. So, what does this leave?

Candidate karst solutes: Szczepaniec-Cieciak et al. [9] calculated the solubility of 17 substances in liquid methane (CH_4) over the range 91-150 K using the Preston-Prausnitz method [12], many of which might be present under Titan conditions. Of those, they found that they were divided broadly into two groups: those of high (10^{-1} to 10^{-4}) molar solubilities (N.B. molar solubilities are generally less than mass solubilities), and those of relatively low molar solubility ($< 10^{-5}$). We infer that the karstic solute is most likely to belong to the first of these groups, as they would facilitate formation of the observed features in time-scales comparable with terrestrial karstic terrains ($\ll 1$ Ma). Acetylene (C_2H_2) is an obvious choice, as its copious formation in Titan's upper atmosphere is well established (e.g. [4]). With an estimated solubility, based on Preston-Prausnitz fits [9] and experimental data [13] of 8×10^{-5} to 8×10^{-4} by mass, it is sufficient to dissolve a 600 m deep depression in ~ 5 ka to 750 Ma. However, acetylene has not been directly observed on the surface, and it is conceivable that it might react with other materials in the atmosphere to form new compounds, such as benzene, which has been observed. That being said, benzene has a relatively poor (5×10^{-9} to 5×10^{-7} by mass) solubility, which would take, at the very least, 20 Ma to form a 600 m depression, and probably much longer.

Other candidates include butane, pentane and neopentane, some of which are much more soluble even than acetylene [9], but their existence is less well established, although predicted by some photochemical models (e.g. butane [4], with solubility $> \sim 3 \times 10^{-4}$ by mass). Furthermore, we cannot rule out the possibility that more complex organons may be formed – chains of simple hydrocarbons, for instance – or that mixtures of many different solids are involved.

Finally, as noted above, if liquid ethane rather than methane is the dominant solvent, then higher solubilities and faster dissolution rates by approximately two orders of magnitude will result. Determination of the composition of Titan's lakes, therefore, should be considered a priority.

A polar cap? Is Titan's karstic solute local to the polar regions, or global? We have no strong evidence

for either. Enhanced evaporation rates at lower latitudes could explain the lack of karstic features there: subsurface drainage of saturated volatiles is insufficient to cause significant excavation. Alternatively, it may be that substantially enhanced precipitation of solids near the pole makes the polar region alone susceptible to the formation of karstic terrain. In this case, we should consider the possibility that the lakes of Titan are incised into some sort of polar cap.

Another issue is whether the soluble layer consists purely of precipitants or whether it includes a fraction of crustal materials, much like the Earth's permafrost. We see little or no evidence of resurfacing by cryovolcanism or impact cratering in this area, and aeolian transport processes (evident from dunes) seem to be primarily at lower latitude and consist of organic materials [14], but some movement of crustal materials to the surface due to fluvial processes may be possible. In general, however, we consider it unlikely that there will be considerable mixing of crustal materials in any precipitated solid layer.

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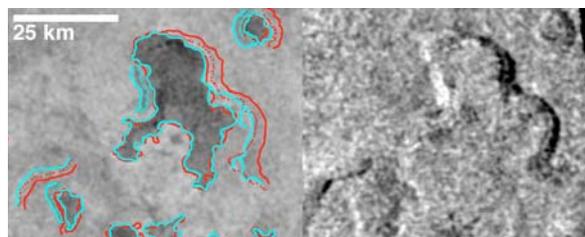


Fig. 1: Source: Kirk et al. (2007). Left, T16 image of lakes near 72°N 127°W , incidence 30° , from left. Shorelines and scarps have been traced in cyan; red traces are same features in T19 image. Right, "magic airbrush" composite (weighted difference) of T16 and T19 images suppresses backscatter variations and reveals subtle slope details.