

KARST ON TITAN. K. L. Mitchell¹, M. Malaska². ¹Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91101, U.S.A. (Karl.L.Mitchell@jpl.nasa.gov). ²SCYNEXIS, Inc., P.O. Box 12878, Research Triangle Park, NC 27709-2878.

Introduction: The Cassini RADAR instrument has revealed a multitude of lakes and lake basins on the surface of Titan, as well as patches of complex “labyrinthian” terrain, both of which are interpreted to be the result of dissolution and/or collapse processes that are karst-like in nature. Here we describe the case for the karstic origin, the chemical context and the broader consequences of such an interpretation.

Titan’s Arctic Lake District: On July 22nd, 2006, the T16 fly-by of Titan gave the first clear glimpses of an active limnological systems on an extraterrestrial world (Stofan *et al.*, 2007). Since then, many additional fly-bys have revealed a North polar terrain covered by 100s of lakes exhibiting a range of morphologies with a non-random distribution, from smaller (a few km) steep-sided quasi-circular depressions at higher elevations in the western hemisphere, to larger seas with rugged shorelines in the eastern. Lake basins with bright (interpreted as drained or very shallowly filled) interiors tend towards lower (<~70 degrees) latitudes and/or higher elevations, hence more arid environs.

Topographic analyses using stereo (Kirk *et al.*, 2007), shape-from-shading and SARTopo (Stiles *et al.*, 2009; Mitchell *et al.*, 2010, 2011) techniques, reveal that: (1) The main population of rimmed lake depressions are up to 100s of metres from rim to floor, and commonly km to 10s of km across; (2) Titan lakes and seas appear not to exist on a simple equipotential surface, but the elevation distribution does appear to be non-random, following approximately the level of the surrounding terrain, which is sloped downwards towards the main seas; and (3) Lakes and surrounding terrain tend to exhibit greater elevation in the western hemisphere (0-180 W) than in the eastern (180 – 360 W). Higher elevations correlate with small, rimmed lakes, and lower elevations with more diffuse seas.

Lake Origins: Lake basins may be formed as a result of the excavatory interaction of liquids on the subsurface (limnogenic) or simply by filling pre-existing depressions (non-limnogenic). On Earth, dense populations of smaller lakes such as we observe on Titan tend to be karstic (dissolution), thermokarstic (periglacial, melting) or glacial in origin. Theoretically, volcanic (e.g. calderas) or impact structures could also be sufficiently plentiful, but we rule these out on the basis of the strong correlation between surface (RADAR dark) liquids and lake basins and the almost uniquely high latitude geographic distribution, in Antarctic as well as Arctic contexts; A bi-directional causal (limnogenic)

relationship between surface liquids and basins seems unavoidable without an unusual and convenient geophysical relationship.

Subjectively, we find the thermokarstic lakes of western Alaska to be strikingly similar photogeologically; numerous circular and sub-circular depressions of the many-kilometer scale, some of which are nested in caldera-like fashion. However, despite a similar geographic context (high northern latitudes), we can find no justification for the kind of insolation thermal processes required to produce thermokarstic melting. Glacial processes are also difficult to justify, due to the lack of sufficiently voluminous bi-phase materials that could exhibit behavior like terrestrial polar ice glaciers; they also lack the elongation one associates with lakes formed from glacial advance and retreat.

Hence, our preferred interpretation for the small, steep-sided and quasi-circular lakes is one of a karstic origin, involving dissolution, collapse and subsurface flow. The contrast between filled and empty lakes may be explained by the relative rates of precipitation, drainage and, if a regional alkanifer exists, infiltration (Hayes *et al.*, 2008). In this case, local variations in lake morphologies may be the result of climatic context (mostly a function of latitude and elevation), or the chemical and structural nature of the underlying terrain. We infer that subsurface flow tends to carry liquids, most likely containing solutes, from higher elevation small lakes to lower elevation seas, which seems consistent with observed topography and the quite massive asymmetry between inferred liquid volumes between western and eastern areas in Titan’s arctic.

Lower Latitude Karst?: The polar lakes are not the only features interpreted to be indicative of karstic processes on Titan. Titan’s Antarctic, although less covered in limnological features, exhibit many of the same morphologies as the Arctic region. In addition, some limited areas of heavily dissected terrain known as “labyrinthic” have been interpreted (Malaska *et al.*, 2010, 2011) as Polygonal Karst-like (closed polygonal walled), Fluviokarst-like (dissected plateau) and Tower Karst-like (remnant ridges terrain). These tend to occur in local areas of high elevation, at mid-high latitudes, fairly close to polar lake regions, and may represent areas of heavy orogenic rainfall and efficient subsurface drainage.

Chemical Considerations: Karstic terrain is fundamentally a result of dissolution geochemistry, which requires a solute-solvent pair. Much like on Earth, the bulk crustal material of Titan, water-ice, is insufficient-

ly soluble in the present liquid alkanes (methane and ethane) over geologically plausible timescales to result in heavily karstic terrains. The unsuitability of water-ice, therefore, means that other more exotic chemistries must be considered. On Earth, most karst forms in regions rich in highly-soluble (up to $\sim 10^{-3}$) carbonate rock, a relatively minor component of the crust, with liquid water acting as the solvent, which offers sufficiently high dissolution rates over the relatively short timescales (decades to 100s of thousands of years) necessary in order to dominate over rates of inevitable tectonic and biotic change. However, it is worth bearing in mind that surface geology is likely to be more stable on Titan, due to the context of a lack of apparent biosphere and plate tectonics, and so karstic features could evolve at much slower rates. Our preliminary estimates suggest that solubilities in the range of 10^{-6} to 10^{-4} , possibly much less, are more than sufficient, on the basis of arguments to be presented at the meeting.

Although karstic processes were not widely predicted on Titan by theoretical modelers, dissolution as an erosional process was explored by Lorenz & Lunine (1996), and should play a critical role in Titan's hydrocarbon cycle, as atmospheric models (e.g. Wilson & Atreya, 2009) and observational data suggests that such exotic chemistries are plausible. These would be delivered via precipitation (airfall), although surface or subsurface processing may be involved. Hydrocarbon production rates (pre-Cassini studies summarized in Lorenz & Lunine, 1996; Wilson & Atreya, 2009) appear to be sufficient to produce such a massive volume; 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 candidates of sufficiently high atmospheric production rates being prone to reacting in the upper atmosphere to form many other more complex materials of variable solubility; The reality is probably a complex smörgåsbord of organics and other materials (Malaska *et al.*, this volume).

Ironically, it is the presence of Titan's thick atmosphere, which makes karstic chemistries possible in the first place, that obscures our ability to detect suitable surface materials present on the surface. Despite some limited apparent success in detection of candidate solutes (e.g. benzene, by Clark *et al.*, 2010), it seems unlikely whether VIMS spectroscopic data of Titan's polar regions will be sufficient to give an unambiguous identification of most relevant surface materials, and so the chemical parameters necessary to constrain models to test this hypothesis are elusive, and we must infer what is possible based on theoretical models and indirect data, which itself is highly limited in resolu-

tion ($> \sim 300$ m/pixel poor signal-to-noise Synthetic Aperture RADAR images).

Discussion: Many other karstic features are likely to be present on Titan, detectable only at resolutions finer than currently available, which will only be discovered by future missions. Assuming that our interpretations are correct, the presence of caves and other subsurface voids seem inevitable; In fact, Titan's low gravity and presumably less tectonically-active environment should allow for greater stable than those on Earth and hence potentially more massive scale.

Although dissolution chemistry is totally necessary for subsurface flow over large scales, it does help to expand and even create hydraulic pathways, and may consequentially enhance flow rates, facilitating horizontal redistribution of liquids over regional-to-global scales. We speculate that subsurface flow has the potential to play an important role in Titan's hydrological cycle, and in forming surficial geological features. Such conjecture may provide an explanation for some observations at sub-polar latitudes (Mitchell *et al.*, 2009), including an apparent enrichment of hydrology-related features in topographic lows, such as Ganesa Macula, and lake basin-like morphologies at the low-latitude Tui Regio.

Future studies will focus on testing models of subsurface flow and characterizing the relevant physical and chemical properties of candidate materials.

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