KARSTIC PROCESSES ON EARTH AND TITAN. K. L. Mitchell[1], M. J. Malaska[1], D. G. Horvath[2] and J. C. Andrews-Hanna[2], [1]Jet Propulsion Laboratory, California Institute of Technology, Mail Stop 183-601, 4800 Oak Grove Dr., Pasadena, CA 91109-8099. Karl.L.Mitchell@jpl.nasa.gov. [2]Colorado School of Mines, Golden, CO.

Karst on Titan: Cassini has revealed that Titan's surface is dominated by products of upper atmosphere photochemistry [1]. Multiple lines of evidence suggest a global average of tens of metres of predominantly organic materials delivered initially by airfall, potentially including acetylene, hydrogen cyanide, acetonitrile and benzene, among others [2,3,4]. The precise mixture is likely a complex smörgåsbord of organics and other materials. Many of these materials are soluble in the alkanes that make of the hydrological system, and so some degree of geological dissolution seems inevitable, opening up the possibility of karst.

Compelling geomorphologic interpretations have been presented for karstic lakes [4,5], as well as poljes, polygonal karst, fluviokarst, tower karst and corrosion plains [3,6]. These encompass all of the karstic landforms that one is likely to be able to interpret at the crude resolutions (>~300 m), ~3% of Titan's surface or 6% if you include lakes. In addition, interpretations of evaporites [7,8] although not classically thought of as karstic landforms, improve confidence that dissolution and redeposition has occured on a large scale.

The evidence suggests strongly that karst is a major contributor to Titan's surface geology, and we infer that many elements of karstic processes on Earth are also active on Titan, opening the possibility of comparative geomorphologic analysis. If so, this finding establishes "karst" as a fundamental geologic process that can occur outside of the specific chemical makeup of Earth. Hence it is timely to review karst models and their potential application to Titan.

Understanding karst: Within the terrestrial literature, the expression *karst* has been used interchangeably to describe a suite of geological processes, materials and landscapes. However, most of the terrestrial community supports the definition as a "style of landscape containing caves [and/or] extensive underground water systems that is developed on especially soluble rocks" [9], including but not limited to limestone, marble and gypsum. This definition applies equally to the different solute:solvent combinations on Titan.

From a dynamic perspective, karst can be thought of as a coupled system of geologic excavation and hydrologic flow. Although critical to karstic development, dissolution alone does not result in karst. Subsurface infiltration and dissolution at depth are the initiators, but suffosion and collapse also play important and at times dominant roles. From a hydrological and speoleological perspective, the evolution of karst involves multiple critical threshold events [9,10 and references therein] in which the mode of subsurface flow changes, typically from slow porous or fracture flow, to far more rapid flow though conduits and caves.

Three phases of speleogenesis are now generally accepted: (1) initiation: initial enlargement of a fracture to a critical size; (2) breakthrough: a fairly sudden transition to rapid dissolution, resulting in growth of an incipient cave into a true cave, and (3) enlargement: growth of a protoconduit/incipient cave to full conduit size [e.g. 11]. As a karstic system progresses through these phases, dissolution becomes less important as faster flow enhances suffosion and collapse, which become the dominate solute transport and landscape forming mechanisms for mature karst. Increases in hydraulic conductivity associated with breakthrough and enlargement may also lower the water table, resulting in either cessation or a fundamental change in karstic development from phreatic (liquid-filled) to vadose (drained or mostly-drained) conduits. Development of karstic systems is further complicated by the strong sensitivity of karstification to local geologic factors. Even small differences in underlying geology, including material composition, microphysical structure and the presence of faults, fractures and folds, can have a profound impacton the evolution, intensity and extent of karstic systems [e.g. 12]. Unfortunately, such complex coupled and highly variable systems are difficult to model in a deterministic fashion based on the physics and chemistry occurring.

That said, there are many commonalities between systems that lend themselves to morphological analysis. The existence of a karst cycle of erosion [e.g. 13] has long been documented, and many of Titan's morphologies could fit into that scheme. Hence, the identification of observed stages in karstic landscape evolution has the potential to give insight into the genesis of the subsurface. Furthermore, understanding of the kinetics of dissolution for solute:solvent pairs can give significant insight. The typical limestone cave has been eroded, collapsed, then redeposited with reprecipitated calcite draperies.

High solubilities does not necessarily result in karstic landscapes. If kinetic rates are too high, then surface development dominates, softening topography without karst initiation. For the deep development characteristic of karst, lower kinetic rates are necessary, so that fluids can continue dissolving infiltrating the subsurface. Furthermore, bulk dissolution does not even appear to be completely necessary, as dissolution of grain margins in a pre-fractured medium can initiate

karstic development via suffosion, as observed in silicate (e.g. sandstone) karstic systems on Earth, which have been referred to as *parakarst* [14].

Contrasts between karst on Earth and Titan: There are several major differences between Earth and Titan that deserve consideration. In particular, the apparently greater scale of karstic features, especially lakes interpreted as collapse dolines [4,5] on Titan is influenced by the lack of plate tectonics, allows karstification evolve over longer geologic epochs, and lower gravity, allowing larger voids before collapse. This stability means that relatively low solubilities and kinetic rates may still result in karst on Titan, although it should be noted that precipitation rates are also thought to be much low, slowing development. The assumed lack of an active biota also means that many of the microbiological processes that can affect karst and cave development are simply not present, which may either enhance or suppress karstification.

Titan's depositional scenario contrasts Earth's, where the bulk of the karstic materials are derived from surface and crustal processes. However, Titan's surface is dynamic, and the estimated production rates, ~ 0.1 m / Ma [1] or less, mean that surface geological processes likely dominate over airfall in shaping straigraphy. Once on the surface, materials would be subjected to erosion, with soluble materials being transported to basins to form evaporites [7]. If exposed to further rainfall or fluids, they may once again be subjected to dissolution. Thus, soluble materials could be regionally concentrated and re-eroded – just like some halite karst deposits on Earth such as those seen in the floor of Death Valley. Hence, sedimentary sequences could be built up on Titan, as on Earth, with periods of evaporite deposition then coverage by insoluble clastics or aeolian deposits. The resulting layer stack could be composed of interbedded material of varying solubility [15]. Base level lowering, climate change to a more humid regime, or broad regional uplift could re-expose this layer stack to erosion [3].

Future studies and recommendations: Our goal is to rein in the number of possibilities for the relevant chemistry and dynamics, by refining our understanding of all of the factors at play, including rainfall and atmospheric deposition rates, surface age constraints (<1 Ga), climate-influencing orbital cycles, and the growing suite of relevant lab-derived solubilities and kinetics. To make sense of these, we intend to embark on a much needed systematic study of how terrestrial karstic morphologies vary as a function of solubility kinetics in order to enhance our ability to make comparative geomorphologic interpretations and potentially add constraints to hydrologic models.

The profound effects of karstification cannot be ignored by hydrological modellers. Unfortunately, models for ground water flow in relatively data-rich terrestrial karstic aquifers have been largely unsuccessful in their application [16], and so implementation in planetary models will necessitate the inclusion of simplifying instructions which limit their utility in prediction and reconstruction. Our recommendation is that subsurface flow models [e.g 17] incorporate vector hydraulic conductivities as a free or loosely constrained parameter, in contrast with scalar conductivities in Darcy flow. Conductivity will tend to enhance over time in a non-smooth manner. In general the vectors will be in the direction of the pre-karstification hydraulic gradient, but bear in mind that it may also be modulated by the presence of geologic discontinuities.

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