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Karstification processes on Titan and on Earth: Denudation rates and timescales

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Abstract

Titan's North polar region is dotted with hundreds of depressions that could originate from karstic-like dissolution of the surface and/or subsurface. On Earth, karstic landforms develop at the expense of a substratum composed of soluble minerals, like carbonates (calcite and dolomite) and salts (halite, gyspum, anhydrite), in contact with water. Solutional denudation rates characterize the rates of lowering of surface with a given composition due to chemical erosion. We compute such rates for Earth's minerals and Titan's solid organic compounds under the relevant conditions. We use these rates to infer possible timescales of karstification on Earth and Titan, and therefore the age of Titan's karstic lakes.

1. Introduction

Titan, Saturn's major icy moon, like the Earth, possesses large bodies of present liquids on its surface under the form of seas, lakes and rivers, and likely of past liquids in currently empty topographic depressions. Lacustrine depressions, be they filled currently or not, are typically isolated, have rounded or lobate contours, as opposed to the larger dendritic seas, and seem to grow by coalescence. Their sizes vary from a few km to a few tens of km in diameter, and they seem to develop in relatively flat areas without visible connection with fluvial networks. Their depths have been evaluated to a few tens/hundreds of meters.

The most likely origin of small lacustrine depression on Titan would be associated with the dissolution of the surface, such as what is seen in karstic or karsto-evaporitic areas on Earth [1]. However, due to Titan's surface physical properties (T=90-95 K) and composition, the materials that would be involved in such dissolution processes are exotic. In karstic terrains on Earth, the solvent is water and the solutes are rock minerals. On Titan, the solvent is mainly composed of liquid methane and/or ethane and the solutes are probably made of solid organic compounds and ices.

We compute the kinetics of surface dissolution using a thermodynamics-climatic model that predicts solutional denudation rates of a surface with a given composition. These rates are computed thanks to estimates of the maximum solubilities associated with a reasonable range of atmospheric precipitation rates estimates for both Titan and the Earth. By analogy with the Earth, inverting the denudation rates allows to estimate rough timescales of karstification processes on Titan, and therefore to date the formation of Titan's depressions.

2. Model description

The solutional denudation rate (DR) describes the rates of lowering of a surface due to chemical erosion only. Our model is similar to that of [2]: DR depends on the solubility (mole fraction at saturation) of the solids in the liquids, on the molar volumes of the solvent and of the solute and on the net precipitation rates fallen down onto the surface.

The solubilities on Titan are calculated using two different theories: an ideal case where the activity coefficients of the solutes in liquids are set to 1, and a regular solution theory based on the Preston and Prausnitz method as simplified by [3]. We only consider pure solids in contact with pure liquids. The molar volumes are estimated using the Rackett equation for the liquids [4] or *ab-initio* calculations (DFT) for some solids.

For Earth's minerals, because the solvent is highly polar and the chemical reaction of minerals in water are known, we use an electrolyte solution theory based

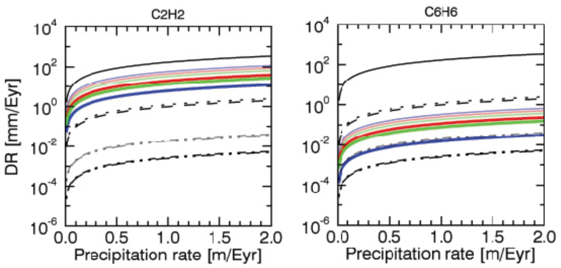

Figure 1: Examples of denudation rates (DR) computed for various solutes/solvents of relevance for the Earth and Titan. Dissociation of minerals in water (black, from least to most soluble: dolomite, calcite, gypsum, anhydrite and halite), acid dissolution of calcite and dolomite (grey), acetylene (C_2H_2) and benzene (C_6H_6) in methane (blue), in ethane (red) and in propane (green).

Table 1: Denudation rates in mm/Tyr assuming the methane precipitation rates of [7] at 80°N.

Name	Formula	Ideal ST	Regular ST
butane	C_4H_{10}	2.52×10^{3}	1.35×10^{3}
hydrogen cyanide	HCN	4.51	1.64×10^{-3}
acetylene	C_2H_2	4.61×10^{2}	4.85×10^{1}
ethylene	C_2H_4	1.37×10^{4}	5.71×10^{3}
methyl-acetylene	C_3H_4	4.43×10^{2}	3.03×10^{1}
vinyl-acetylene	C_4H_4	3.60×10^{1}	1.23×10^{1}
dimethyl-acetylene	C_4H_6	8.06	4.23
benzene	C_6H_6	2.62	1.21×10^{-1}
acetonitrile	CH_3CN	1.33×10^{1}	1.95×10^{-3}
acrylonitrile	C_2H_3CN	1.99×10^{2}	6.50×10^{-1}
propionitrile	C_2H_5CN	3.73×10^{2}	3.37
cyanogen	C_2N_2	1.20×10^{1}	2.00×10^{-1}
carbon dioxide ice	CO_2	6.28	5.88×10^{-1}

on the computation of the molalities of species given their equilibrium constants of reaction. The activity coefficients are computed using the Debye-Huckel extended equation [5]. We also include the acid dissolution of carbonates due to CO_2 gas in the model [6].

3. Results

Dissolution on Titan is highly efficient (Fig. 1 and Table 1). Most simple hydrocarbons in contact with liquid hydrocarbons react like salts in water. This means that denudation rates are on the order of a few millimeters per Titan year at latitudes poleward of 60°, assuming the methane precipitation rates of [7]. Benzene, nitriles and carbon dioxide react more like carbonates, with denudation rates up to a few hundreds of microns per Titan year.

Given this range of denudation rates, and assuming that Titan's climate remained unchanged in the recent past, one can investigate the denudation rates for a mixed layer of organic compounds (neglecting tholins), the composition of which is given by photochemical production rates of organics in the atmosphere according to different models [8, 9, 10]. Such compositions for the surface layer would lead to denudation rates on the order of at least a few mm per Titan year, whatever the model, the latitude and solution theory. This implies very recent ages for Titan's karstic-like depressions, ranging from a few thousands up to a few million Earth years.

These extremely recent ages are not surprising given the fact that these mixed organic layers would be mainly composed of simple hydrocarbons/salt-like materials and that terrestrial caves carved in salts are commonly developed in only a few thousands to tens of thousands years (for comparison, carbonates karsts develop with timescales on the order of a few hundreds of thousands up to a few million years, depending on the climate). The young age of Titan's lacustrine depressions is also in good agreement with the youth of the surface as inferred from crater counting [11].

Further work will include the effect of the almost insoluble tholins-like compounds and rains in equilibrium with the atmosphere to give more realistic age estimates.

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