

PHYSICO-CHEMICAL STATE OF TITAN'S SUBSURFACE LAYERS Janusz Eluszkiwicz and David J. Stevenson, 170-25 Caltech, Pasadena, CA 91125

I. INTRODUCTION Recent radar observations of Titan by Muhleman et al. [1] seem to preclude the presence of a global hydrocarbon ocean. On the other hand, according to the photochemical model by Lunine et al. [2] a reservoir of liquid methane/ethane corresponding to an ocean ~ 1 km thick should be present on Titan. In order to reconcile observation with theory, we begin to explore the possibility that liquid hydrocarbons are stored in the regolith beneath Titan's surface. Assuming a porosity of ~ 30% this would require a regolith thickness of ~ 3 km. Two ways of creating this "regolith" come to mind: 1. megaregolith created during the period of heavy bombardement which then withstood destruction by stress and temperature driven compaction and/or 2. an "aquifer" (or rather "methanifer") created by cavernous weathering, i.e dissolution of water ice in liquid methane/ethane.

II. COMPACTION OF THE REGOLITH. Let us assume that a regolith > 3 km thick was somehow formed early in Titan's history. Now let us inquire whether this regolith could have withstood compaction over ~ 4 Gyr. The main process driving compaction at the relevant pressures is power-law creep [3]. The timescale for compaction is then given by

$$\tau^{-1} \equiv -\dot{\phi}/\phi = \frac{3.1(1-\phi)}{\sqrt{C}\phi} \exp\left\{Q\left(\frac{1}{T_0} - \frac{1}{T}\right)/R\right\} \left\{\frac{p}{\sigma_0} \frac{C}{3(1-\phi)^2}\right\}^n \dot{\varepsilon}_0$$

where ϕ is the porosity, $C = \phi_0/(\phi_0 - \phi)$, ϕ_0 is the uncompressed porosity ($\phi_0 = 36\%$ is assumed here), $Q = 36$ kJ mole⁻¹, T is the temperature, R is the gas constant, $p = (\rho_i - \rho_l)gz$ is the effective hydrostatic pressure at depth z (ρ_i and ρ_l are the densities of water ice and liquid hydrocarbons, respectively), and $n = 4.7$. This particular form of the densification rate was obtained by matching the preexponential factor A in the general creep law to the lowest strain rate ($\dot{\varepsilon}_0 = 3.5 \times 10^{-7}$ s⁻¹ at $\sigma_0 = 110$ MPa) at the lowest temperature ($T_0 = 140$ K) in the experiments by Kirby et al. [4] with the average values for Q and n given by Kirby et al. The temperature at depth z is calculated from the equation $F = -k^* \frac{dT}{dz}$, where F

is the heat flow in ice and k^* is the effective thermal conductivity of the porous ice calculated by means of the mean-field theory. The surface temperature $T_e \equiv 94$ K. The compaction timescale at $z = 3$ km as a function of F is plotted in Fig. 1. If the liquid in the pores is convective $F = 0$, whereas in the conductive state, $F \sim 5$ mW m⁻² at present and ~ 30 mW m⁻² early in Titan's history. Since porosity in an impact-created regolith is likely to be in the form of macroscopic fractures, with a corresponding large permeability, porous or even pure liquid convection can be expected, and there seems to be no problem in preserving a 3 km regolith, provided it was formed in the first place. Fig. 1 suggests that any accretional porosity was quickly destroyed during the period of enhanced heat flow. Existing models of impact regolith on Ganymede predict thickness < 1 km [5]. However, the latter estimate refers to the ejecta blankets associated with the present-day craters and is probably only a lower limit to the thickness of the impact-generated megaregolith.

III. CAVERNOUS WEATHERING It is possible that "porosity" increases rather than decreases with time deep beneath the surface. The physical process is as follows. The solubility of water in liquid hydrocarbons may increase with pressure.

Accordingly, water dissolves in the deeper regions of the liquids and redeposits near the surface of the liquid (presumably beneath the physical surface of Titan). The extent of this process can be estimated as follows. Let C_0 be the zero-pressure solubility of H_2O in the liquid hydrocarbons mixture. The actual solubility is $C_0 \exp(p\Delta v/kT)$, where p is the hydrostatic pressure in the liquid, $\Delta v = v_i - v_l$ (v_i and v_l are the specific volumes per molecule of H_2O in ice and liquid, respectively), k is Boltzmann constant, and T is temperature (almost exactly isothermal at ~ 94 K in the convecting fluid, as discussed above). For a liquid depth \sim a few km, $p \sim 100$ bar, and $p\Delta v/kT \sim 10^{-2}(\Delta v/v_i)$. The erosion of ice in a liquid region of subsaturation ΔC proceeds at velocity $\sim D(\Delta C/\delta)$ where D is the diffusivity of H_2O in the liquid and δ is the boundary-layer thickness in the convecting system. Plausibly, $\delta \sim \sqrt{Dt}$, where $t \sim \delta_{th}^2/k$ is the thermal convection characteristic timescale governed by the requirements $F = k\Delta T/\delta_{th}$ and $\text{Ra} \equiv g\alpha\Delta T\delta_{th}^3/v\kappa \approx 10^3$ (α = coefficient of thermal expansion, v = kinematic viscosity, κ = thermal diffusivity) [6]. This analysis corresponds to erosion on a horizontal surface and is more conservative than erosion on a vertical surface [7]. It predicts $\delta_{th} \sim 10$ cm, $\Delta T \sim 10^{-3}$ K and an erosion velocity $v \sim 10^{-4} \Delta C \text{ cm s}^{-1}$ (provided ΔC is very small). If we consider liquid channels of width l separated by a horizontal distance L , so that porosity $\phi \sim l/L$, then we conclude that $\dot{\phi} \sim v/L$ in the deepest regions. Of course, the mean (depth-averaged) ϕ is zero since water is conserved. The value of C_0 is uncertain since it has only been measured at 112 K [8] where it is 6×10^{-5} , but 6×10^{-6} is a reasonable estimate at 94 K if $C_0 = \exp(-\Delta E/kT)$. If $\Delta v \sim 0.1 v_i$, then $\Delta C \sim 10^{-8}$ to 10^{-9} and $\tau \equiv \phi/\dot{\phi} \sim 10^8$ years for $l \sim$ meters. Obviously, there is much uncertainty here, but plausible parameter choices allow for a large amount of cavernous weathering over geologic time. This may contribute to the solution of the regolith formation problem discussed above. A model that relies exclusively on cavernous weathering has one major drawback: the channels might be closed off completely at the top of the fluid columns where H_2O is preferentially deposited. It is essential that some channels remain open so that CH_4 is resupplied to the atmosphere. However, only small openings are needed for vapor escape.

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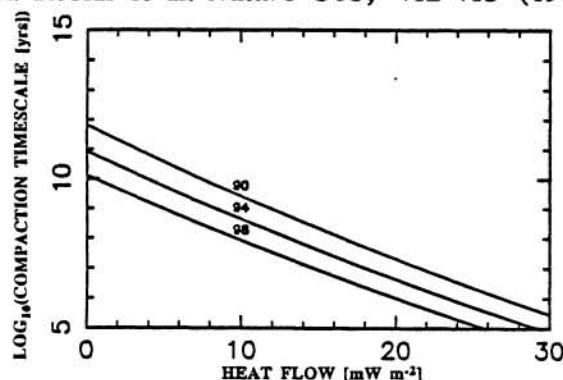


FIG. 1. The timescale of compaction due to power law creep at $z = 3$ km (depth of the regolith needed to store ~ 1 km of liquid hydrocarbons) as a function of heat flow F . The value $F = 0$ corresponds to convection in the liquid. The curves are labeled by the value of surface temperature.