Titan's Subsurface Alkanology S. Vance, C. Sotin, M. Choukroun, and K. Mitchell. Jet Propulsion Laboratory, California Institute of Technology (svance@jpl.nasa.gov, 183-401, 4800 Oak Grove Dr., Pasadena, CA 91109)

Introduction: To maintain Titan's atmospheric methane in the absence of replenishment by impacts, a subsurface reservoir of alkanes is needed; lake volumes, estimated at more than $3x10^4$ km^3, are insufficient to sustain Titan's atmosphere over geological time [1].

If impacts are not replenishing Titan's methane, the global reservoir is likely static. Serpentinization—H_2-producing hydroxylation of anhydrous Mg- and Fe-bearing olivine suggested as a source for Titan's methane [2]—could occur only prior to or during Titan's differentiation, as high hydrostatic pressures (>500 MPa) at the base of the H_2O layer in a differentiated Titan should prevent fluid access to rock through the closure of microfractures [3].

Burial through cryovolcanism or other means may account for the relatively low ethane abundance observed by the Huygens probe; only a 2.3 km-thick layer of 10% porosity is needed to store the missing ethane as a 3.3:1 mixture of liquid:clathrate [4]. Ethane-nitrogen-methane clathrates are denser than water ice and might be expected to become buried through cryovolcanism [5]. Dissociation of methane clathrates in a source region 3 km in depth and diameter would supply ~10^{13} kg of CH_4, sufficient to maintain the atmospheric supply if such activity occurs at least every few 1000 yr [6].

Titan's Lakes: The broad distribution of lake-like features above 55º N latitude is consistent with a climate cycle that feeds fluvial activity [7,8,9] Many lakes have rounded shorelines and are relatively lacking in tributaries, indicating that subsurface infiltration plays a role; an absence of observed changes in lake shorelines is consistent with either a water-table equivalent or a solid barrier at a characteristic depth inversely proportional to the effective porosity φ [10].

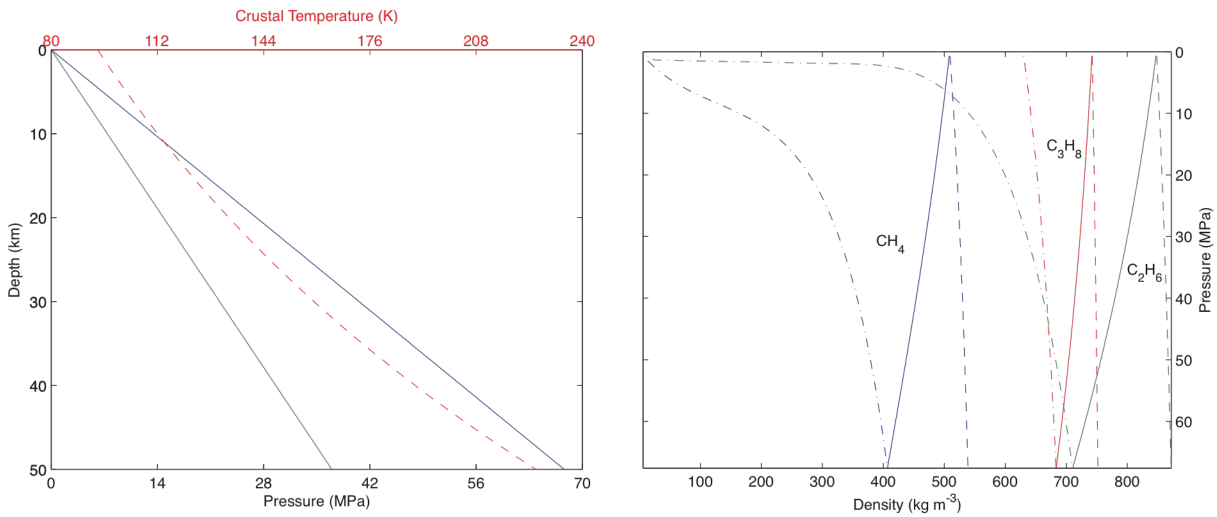
Subsurface Alkanology in Titan's Cryosphere: Titan's thermally conductive crust can be defined as the upper ~20 km of ice where solid state convection cannot occur; it is estimated that crustal temperature increases from 94 K at Titan's surface to ~260 K [11]. The upper crust is likely porous or fractured, and susceptible to transmission of liquids under a pressure gradient [12]. Permeabilities in terrestrial hydrologic systems are often anisotropic and dominated by horizontal flow, a trait dependent on sheeting of sedimentary clays. One might reasonably question assumptions that Titan sediments will behave similarly. The inference of an unsaturated zone lateral to the lakes implies that capillary [e.g., 13] or preferential flow models [*e.g.,* 14] may be more appropriate. Capillarity implies surface tension effects, however, and it is not obvious that such effects exist for non-polar alkanes flowing through ice or hydrocarbon matrices. These subtleties underscore the need for an understanding of Titan-like alkanological systems.

The list of representative Titan surface materials includes ice—the likely bulk composition—various clathrates in the subsurface, and analogues for fluvial sediment materials. *Huygens* lander penetrometry results [15] and subsequent work with laboratory simulants [16] suggest sand or silt-like materials for the latter, but little can be said as to whether these are composed of pure ice or granular hydrocarbon solids.

Interactions Among Alkanes: Methane, ethane, and propane are likely present at Titan's surface as miscible liquids. Larger alkanes may be present as well. Differences in thermodynamic properties for these various liquids may lead to novel geophysical phenomena. Examining single-phase densities for methane, ethane, and propane (Figure 2) illustrates some of the behavior that would occur if these fluids behave immiscibly. Densities are calculated along the cryotherm (the pressure temperature profile of the conductive layer of Titan's ice) and at upper and lower temperatures (94 K and 210 K, respectively; Figure 1) using a Matlab implementation of the Peng-Robinson equation of state [17], formulated for hydrocarbons in terms of their critical parameters and characteristic acentric factors [18].

Densities vary by up to 50%, mostly due to temperature effects, illustrating a potential for complex fluid flow in Titan's subsurface. The present example shows a possibility for concentrating propane at 15 km depth, where its density is comparable to that of ethane (in reality, miscibility will lead to more complex behavior). The trend to zero ethane and methane at bottom temperatures suggests cycling from depth would cause them to vaporize on depressurization, possibly forming geysers [19]. Propane would remain liquid.

Equations of State: Experimentally robust and self-consistent equations of state for aqueous materials and hydrocarbons under Titan's surface and interior conditions of pressure and temperature. For example, experimental measurements of methane and ethane solubilities in water near their critical points suggest the capacity of Titan's ocean for these molecules is more than a factor of four greater than would be predicted from Henry's law [20]. Peng-Robinson equations of state for hydrocarbons can be applied to liquid-vapor systems in Titan, but these too require care in



Figures 1 and 2. Depth-dependent pressure (solid) and temperature (dashed) in Titan's crust (left) in terms of overlying liquid (alkanes; lower) and solids (ices; upper), based on average densities for ice and liquid ethane-methane mixture under surface conditions. Single-phase densities for methane, ethane, and propane (right) are calculated using the Peng-Robinson EOS implementation for Matlab [17]. Solid lines are calculated along the cryotherm, whereas dashed and dash-dotted lines are calculated at upper and lower temperatures (94 K and 210 K, respectively). Densities vary greatly, illustrating a potential for complex fluid flow in Titan's subsurface. The present example shows a possibility for concentrating propane at 15 km depth, where its density is comparable to that of ethane (in reality, miscibility will lead to more complex behavior). In the present scenario, convective cycling of ethane and methane cycling from depth would cause them to vaporize on depressurization, whereas propane would not.

evaluating self-consistency and consistency among the various sets of experimental data [26,27].

Discussion and Conclusions: Titan's reservoir of alkanes is probably not being regenerated by water-rock interactions unless replenished by impacts; in that case, subsurface reservoirs are needed to sustain the atmosphere over long timescales. Changes in lake shorelines indicative of subsurface transport have not been revealed in Cassini observations to date. Understanding multi-phase flows in Titan's porous upper crust may be essential for constraining material budgets and heat transport. Published experimental data and related equations of state for alkanes are sufficient for modeling single phase processes, but reliable multi-phase properties and associated flows depend on properly representing fluid-vapor behavior, especially near critical pressures and temperatures. Particularly needed are experimental constraints on solid-liquid-vapor interactions for Titan-like materials, including, especially, permeability of ices to liquid hydrocarbons.

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Acknowledgement: This work was performed at the, California Institute of Technology and Jet Propulsion Laboratory (JPL) under a contract with the National Aeronautics and Space Administration (NASA), with support from the Icy Worlds node of NASA's Astrobiology Institute (08-NAI5-0021).