A SLUSHBALL (SNOWBALL) TITAN EVENT FROM A METHANE-DEPLETED ATMOSPHERE.

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Introduction: Titan is the only planetary body in the present-day Solar System other than Earth that sustains a liquid volatile on its surface and may have similar yet unique evolutionary processes to Earth. Hydrocarbon lakes composed of methane and ethane currently exist on the surface because of the frigid surface temperatures near ~94K [1]. Titan's climate may have fluctuated in its past from changes in Saturn's orbital eccentricity, Titan's axial tilt, and geochemical alterations to Titan's atmosphere, which could have cooled Titan's surface temperature for a period of time to as low as ~81K [2-3]. This low-temperature period may have altered the physical state of Titan's surface chemistry, such as the existence of liquid nitrogen (N_2) and solid methane (CH_4) in surface reservoirs. The possibility of Titan enduring surface changes in paleoclimates posits the question if Titan can withstand a type of "snowball-like" scenario similar to the Earth.

Titan and Earth's "N_2+Volatiles" Atmospheres: The Earth is believed to have undergone global glacial intervals dubbed "snowball Earth" events where glacial ice covered land and ocean at low latitudes that had essential geochemical, geophysical, and biological impact on the planet's evolution [e.g. 4-6]. The runaway ice-albedo feedback is primarily explained from the removal of greenhouse gases from Earth's nitrogen-dominated atmosphere into surface and subsurface reservoirs thus cooling Earth's surface temperature.

Similar to Earth, Titan's atmosphere is mainly composed of nitrogen, with smaller concentrations of methane, creating a greenhouse effect at the surface. A depletion of methane from Titan's atmosphere would require surface and subsurface reservoirs to store condensed liquid CH_4. Based on total CH_4 concentration estimates in Titan's global atmosphere-surface cycle, subsurface reservoirs of liquid CH_4 likely exist and sustain surficial hydrocarbon lakes [7]. The combined outgassing suppression and storage of CH_4 in subsurface liquid "alkanofers" in the porous water ice crust, principally near the polar regions, cools the surface temperature analogous to Earth's ice-albedo feedback.

Abrupt volcanic outgassing of greenhouse gases into Earth's atmosphere likely ends snowball Earth episodes by initiating a period of substantial warming. It would therefore be expected that CH_4 outgassing into Titan's atmosphere (since methane is the primary volatile in Titan's N_2-dominated atmosphere) ends a period of cooling by triggering greenhouse warming conditions to the surface.

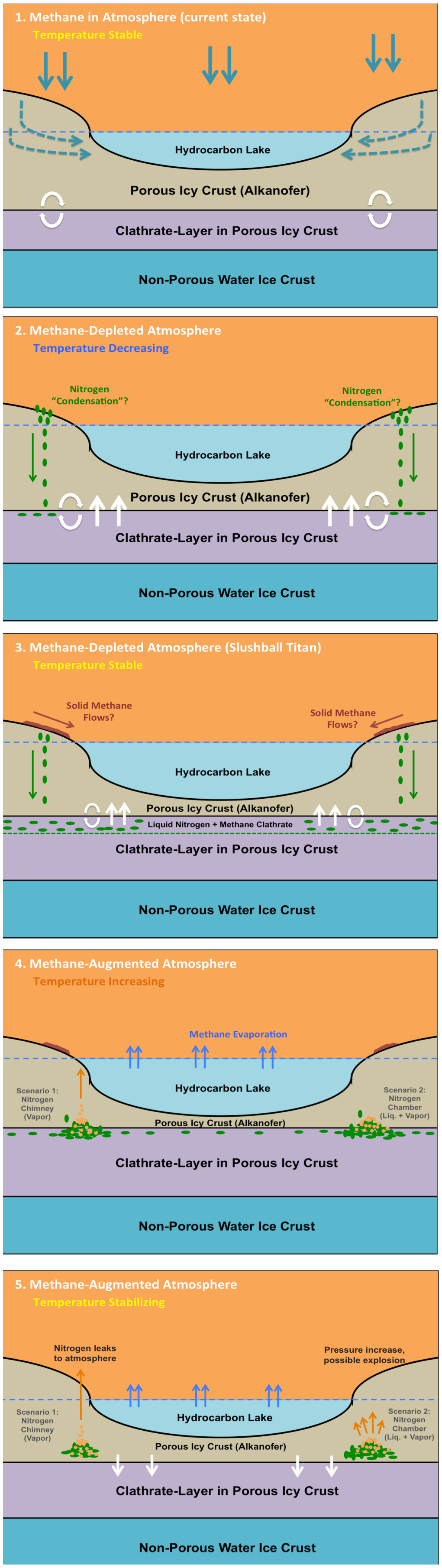
A Slushball (Snowball) Titan: Considering that CH_4-cycling on Titan is analogous to Earth's cycling of water and greenhouse gases, below is a proposed description of a snowball Earth-like occurrence on Titan. This scenario in Titan's paleoclimate is being called a "slushball Titan" since water ice composes the crust and is not the primary volatile within the N_2-dominated atmosphere. Figure 1 illustrates the proposed Slushball Titan event from initiation to expiration.

Initiation of a Slushball Titan. Titan's global CH_4 is stored as atmospheric gas or surficial liquid in hydrocarbon lakes or subsurface alkanofers (Fig.1.1). The adopted structure of Titan's upper crust is a porous water ice medium that resides above a region of methane clathrates and a non-porous ice layer [8]. During a CH_4-depleted atmosphere (as stated above), most-to-all CH_4 from the atmosphere condenses to rain and is stored in surface reservoirs such as hydrocarbon lakes and alkanofers (Fig.1.2). Titan's ambient surface temperature cools because of the CH_4 depletion from the atmosphere.

Surface Features of a Slushball Titan. There are two primary geochemical processes and features that are proposed to ensue during a Slushball Titan episode: (1) atmospheric N_2 condensation in subsurface reservoirs, and (2) surficial CH_4 freezing (Fig.1.3).

First, atmospheric N_2 may condense and form on the surface as a low-viscosity liquid from the cooler surface temperatures [9]. The denser liquid N_2 can descend through the less dense porous water ice medium of the upper crust to the methane clathrate layer. It seems plausible that sufficient concentrations of liquid N_2 could coalesce into miniature pools or chambers depending on the total concentration of liquid N_2 and the duration of the surface cooling event.

Second, surficial CH_4 freezing may occur at the surface as a result of the cooler surface temperatures. Crystalline CH_4 at surface temperatures near 81K acts as a sticky, viscous non-Newtonian fluid [10-12]. Liquid CH_4, in relation to "solid" crystalline CH_4, does not erode water ice readily due to its lower density. The non-Newtonian behavior and higher density of solid CH_4 on Titan has an increased potential to gouge the water ice surface, albeit at a slower erosional rate compared to glacial erosion on the Earth [3]. Solid CH_4 may therefore be a potential candidate, other than methane rain, for forming the carved surface sluices.



Methane-Augmented Atmosphere. The slushball Titan episode would be expected to end, or expire, similarly to how a snowball Earth event ends: an abrupt outgassing of greenhouse gases that warms the atmospheric surface temperature. On Earth, volcanic gases such as CO_2 and CH_4 are emitted back into the atmosphere that initiate a greenhouse warming. On Titan, CH_4 must be augmented to the N_2-dominate atmosphere to introduce a period of global warming.

Based on two recently proposed models of Titan's geological processes [9,13], it is suggested that N_2 bubble formation and subsurface pressure increase of greenhouse gases leads to surface exsolution of CH_4 that initiates surface warming (Fig.1.4 and Fig.1.5). An experimental procedure demonstrates that ethane mediated titration or temperature-induced stratification can lead to N_2 bubble formation on Titan [13]. It is assumed here that the liquid N_2 that descends to the methane clathrate layer during a slushball Titan scenario could form N_2 bubbles in the lower porous icy medium. These bubbles can then entrain CH_4 during ascent from the clathrate layer to the surface prior to exsolution.

The N_2+CH_4 bubbles may leak to the surface in the form of gaseous chimneys or as an explosion-like blowout from a build-up in pressure, similar to the scenarios proposed to have occurred on Earth's Arctic seafloor [14]. The explosion-like events of vaporous N_2 may be the cause of rimmed craters observed at the surface, as described in detail by [9].

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Figure 1: An illustration of a slushball Titan event from initiation to expiration. Fig.1.1 depicts the currently observed state of Titan's surface. Fig.1.2 and Fig.1.3 shows the surface temperature decreasing and the result of a slushball Titan. Fig.1.4 and Fig.1.5 portrays the methane-augmented warming from subsurface reservoir exsolution scenarios to the atmosphere.