INTRUSIVE AND EXTRUSIVE CRYOVOLCANISM AND THE COMPOSITION OF TITAN'S ICY CRUST Lauren R. Schurmeier[1], Andrew J. Dombard[1], Jani Radebaugh[2] Michael Malaska[3], [1]Dept. of Earth and Environmental Sciences, University of Illinois at Chicago, Chicago, IL 60607 (lschur2@uic.edu), [2]Brigham Young University, Provo, UT, [3]Jet Propulsion Laboratory, Pasadena, CA.

Introduction: Titan, the orange of the solar system, gets its iconic haze from the photochemical breakdown of atmospheric methane and nitrogen. It is estimated that the current amount of atmospheric methane should be depleted within 10 – 100 My [1, 2]; hence methane replenishment is presumed to occur. Replenishment may be accomplished by delivery from large bodies of as-yet undetected near-surface liquid methane reservoirs more extensive than the currently visible lakes and seas, direct atmospheric insertion due to cryovolcanic eruptions [3], or release from near surface methane clathrates. Modes of methane clathrate release include substitution with ethane liquids [4], destabilization of methane clathrates around near-surface intrusive cryovolcanism [5], or destabilization during episodes of internal convection [6]. All modes requiring methane clathrate as a reservoir necessitate that a significant portion of Titan's icy crust should be composed of methane clathrate.

Unfortunately, these processes have not been directly observed. In fact, there is no direct evidence for large enough bodies of methane nor is there direct evidence for the existence of methane clathrates. While putative cryovolcanic constructs has been tentatively identified on Titan [3], the interpretation of landforms as cryovolcanoes has been debated [7]. Here, we aim to study specific topographic loads - large isolated plateaus and dome shaped Labyrinth terrains - to determine if they could have cryovolcanic origins, and investigate if they can form within or be supported by a water ice-rich or methane clathrate-rich ice shell.

Areas of Interest: We identify two large plateaus and several dome shaped radial Labyrinth terrains in Titan's mid-latitudes. The plateaus are radar bright, ~600 m tall, 200-350 km wide, heavily eroded, and include down-slope channels (Fig. 1). Our previous study concluded that they cannot be supported by Airy isostasy or pushed up from below, but instead may be loads within or on the lithosphere by intrusive or extrusive cryovolcanism [8].

Several dome shaped features, informally referred to as "radial Labyrinth Terrains" are found clustered in the mid-latitudes (Fig. 1). As described in [9], they are elevated and appear dome-like, circular in planform, have a strong radial dissection pattern, and are bordered by Undifferentiated Plains units. Their assumed composition is organic-rich based on radar emissivity, similar to the surrounding Undifferentiated Plains. Based on their shape, clustering, and dimensions, we interpreted them as uplifted and later dissected plateaus composed of organic sedimentary materials (Undifferentiated Plains) that are the surface expression of large subsurface laccoliths [10].

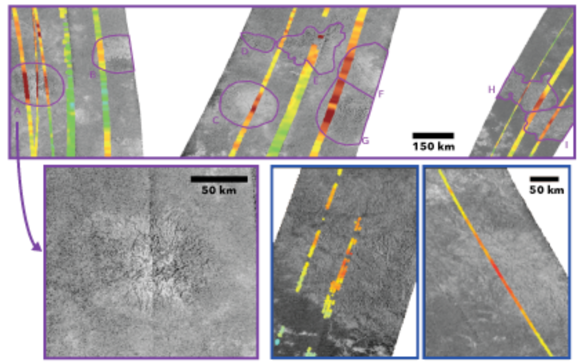

Figure 1: Cassini SAR images of the radial Labyrinth terrains (outlined in purple on top, with a closer view of A on bottom left) and plateaus (bottom center and right). SARTopo data are colorized with warm and cool colors to indicate high and low elevations.

Methods: *Plateau Support.* Following our previous work [8], we investigate the viscoelastic evolution of plateaus using the finite element method. The initial plateau shape is 600 m to 1 km in height and possesses an axisymmetric Gaussian shape. We run thermal simulations for an all water ice crust and an all methane clathrate crust (which has a significantly lower thermal conductivity [11]), then pipe the results into a mechanical simulation, applying a water ice rheology (grain boundary sliding, diffusion creep, and dislocation creep for a grain size of 1 mm) or a methane clathrate rheology (creep law from [12]). Each simulation is run for a simulated time of 3 Gyr.

Laccolith Scaling Relationship. A recent study by Manga and Michaut [13] explained Europa's lenticulae (pits, domes, spots, chaos) as the formation of saucer-shaped sills that form laccoliths (of radius r) near the base of the elastic lithosphere (extending to depth d), where $r \approx 2.4d$. Building on this, we have previously hypothesized [10] that Titan's radial Labyrinth terrains formed as cryovolcanic (water) intrusions that rose to the base of the lithosphere where it becomes easier to spread horizontally than vertically. The laccolith spreads horizontally to an extent determined by the thickness of the load above it, then inflates, flexing the overlying ice and thin organic-rich surface sedimentary cover (Undifferentiated Plains). As high-standing organic deposits, the domes will more easily erode than the surrounding regions, resulting in labyrinth or maze-like surface features through karstic formation processes [14, 15, 16]. Here, we apply the same scaling relationships to the selected radial Labyrinths. We measure their longest diameters using ArcGIS in order to constrain the thickness of the elastic lithosphere.

Yield Strength Envelope. To determine if the laccoliths formed near Titan's brittle-ductile transition (near the depth of the elastic lithosphere), we have created a Yield Strength Envelope (YSE) for ice and methane clathrate ice shells. The brittle-ductile transition is found by plotting the brittle failure curves for water ice in compression and tension [17], and identifying the depths where they intersect with the dominant ductile mechanism curve for 100% water ice (including grain boundary sliding, dislocation creep, and diffusion creep) [18], and the ductile creep curve for 100% methane clathrate [12]. Finally, we explore YSE's for water ice with different thicknesses of clathrates acting as an insulating layer above it. The parameters used include: a surface temperature of 94 K, heat flux of 4 mW/m^2, grain sizes of 0.1 and 10 mm (bracketing a likely range of grain sizes), ice and clathrate thermal conductivities of $k = (651 W/m)/T$ and $k = 0.5$ W/mK respectively, and strain rates of $1x10^{-18}$ to $1x10^{-13}$ s^{-1}.

Results: *Plateau Support.* We confirm that the large plateaus can be supported by a water ice lithosphere [cf. 8]. The surface topography of the plateau minimally sags as the lithosphere flexes under the imposed load (Fig. 2). In stark contrast, the simulations using methane clathrate are incredibly unstable compared to pure ice, indicating that ice can support large plateaus but clathrates cannot.

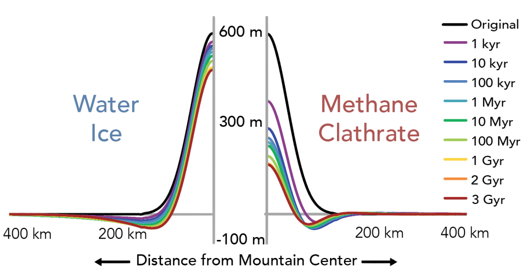

Figure 2: The viscoelastic evolution of a large plateau made of ice (left) or methane clathrate (right).

Laccolith Scaling Relationship and Titan's YSE. The diameters of the Labyrinths imply an intrusion depth of 29 – 33 km [9]. The YSE of a 100% ice crust suggests a brittle-ductile transition of 21-50 km (Fig. 3). The YSE of 100% methane clathrate implies a transition of 9-14 km. Restricting the clathrate to a surface layer 5 km thick [cf. 4] makes the underlying water ice too warm for elastic support; therefore the brittle-ductile transition is essentially at the top of the water ice/clathrate interface around 5 km depth (not shown).

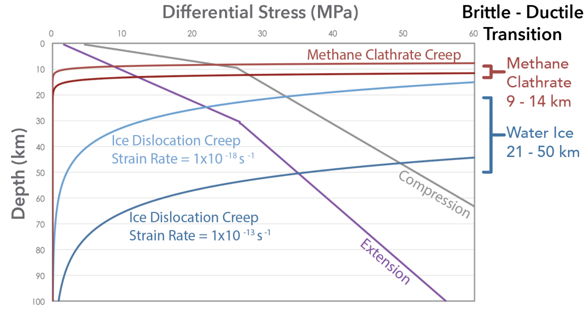

Figure 3: Titan's Yield Strength Envelopes. The brittle-ductile transition is 21-50 km for ice (blue) and 9-14 km for methane clathrate (red) ice.

Discussion: Results from our modeling and scaling relationships show that despite its greater strength relative to water ice, methane clathrate shells are too thermally insulating, resulting in thinner lithospheres. Thin lithospheres cannot support large plateaus; they must be supported in a predominately water ice-rich shell.

Similarly, the YSE's for water ice show a brittle-ductile transition likely around 30-40 km deep, which agrees with the intrusion depth predicted if Titan's radial Labyrinths are in fact laccoliths [cf. 10]. Because the width of the laccolith scales linearly with the thickness of the lithosphere, lithospheres of a thickness consistent with a methane clathrate shell or thick clathrate surface layer would yield Labyrinth terrains a factor of several smaller than what is observed.

Conclusions: Our simulations and scaling relationships argue that Titan's ice shell at these locations must be predominately water ice, not predominately methane clathrate, because the thermal conductivity of methane clathrate results in a lithosphere that is too thin to explain large plateaus and dome shaped Labyrinth terrains. This finding suggests that atmospheric methane recharge may need to come from elsewhere.

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