TITAN'S ISOLATED MOUNTAIN PLATEAUS: INVESTIGATING POSSIBLE SUPPORT MECHANISMS AND CRYOVOLCANIC ORIGINS Lauren R. Schurmeier[1], Andrew J. Dombard[1], Jani Radebaugh[2], [1] Dept. of Earth and Environmental Sciences, University of Illinois at Chicago, Chicago, IL 60607 (lschur2@uic.edu), [2] Brigham Young University, Provo, UT.

Introduction: For an icy satellite, Titan's topography is surprisingly curious. The topographies of similarly sized Ganymede and Callisto, along with the other moons of Saturn (excluding the special case of Iapetus) are dominated largely by impact craters and in some cases large extensional faults and fractures. Quite to the contrary of this trend, regions of high topography, "mountains", and mountain chains were identified early in the *Cassini* mission in SAR imagery and radarclinometry [1]. More recently, several large topographic features were identified in a global topographic map of Titan constructed from interpolated SARTopo and altimetry data [2]. Four topographic rises, at least 200 km wide and 600-700 m above the surrounding terrain were identified in an arc-like shape in the southeastern quadrant of Titan (Fig. 1).

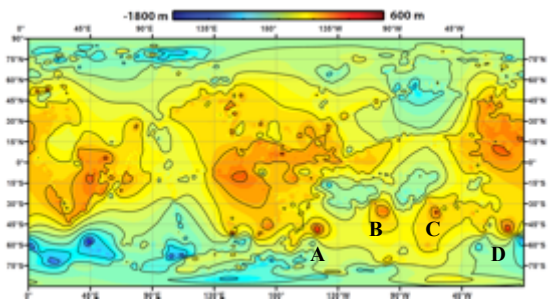

Figure 1: Interpolated topographic map of Titan from [2]. The four topographic rises are labeled: A, B, C, and D.

These large, isolated, topographic rises, which we term "mountain plateaus", are perplexing because of what Titan's outer layers are made of: a solid icy crust that overlies a slightly denser liquid water ocean. All large-scale topography such as mountains requires a mechanism of support. On Earth, large mountains are supported by Airy isostasy, in which large topographic highs have larger low-density roots pushing into the denser mantle for buoyant support. On Titan, the roots of mountains would need to be very large to provide buoyant support because of the small density contrast between ice and water, completely analogous to the 10% of an iceberg that stands above the water's surface on Earth. For Titan, such a root may not be able to provide buoyant support because the high temperatures in the lower portion of the ice shell (approaching melting) means the ice will be viscously weak and will not be able to transfer the support to the surface, analogous to the evolution of large impact basins on Mars [3]. Here, we investigate the long-term stability of Airy isostatic support for Titan's mountain plateaus and discuss alternative support and formation mechanisms.

Methods: To determine if the four isolated topographic rises are in fact mountains and not simply artifacts of interpolation of sparse topographic coverage, we examine the available *Cassini* SAR imagery for morphological indications of mountainous regions (radar bright or rough surfaces and fluvial features) and SARTopo data [4] for evidence of large topographic highs relative to the background topography.

Locations A and D (Fig. 2) are radar bright and fluvially dissected throughout the topographic high, and several large fluvial features (interpreted as river channels) appear to originate within them and flow south. Using SARTopo data, we estimate that the mountain in location A is 600 m tall and 200 km wide, and location D is 600 m tall and 350 km wide.

Unlike A and D, location B shows some signs of fluvial dissection and radar-bright regions, but they are not localized to the topographic high in the global topography. Plus, the SARTopo data do not show a clear mountain shape, so we interpret this topographic high to be a product of the interpolation. Location C has one strip of altimetry data that is mountain-like; however, it lacks SAR imagery needed for confirmation.

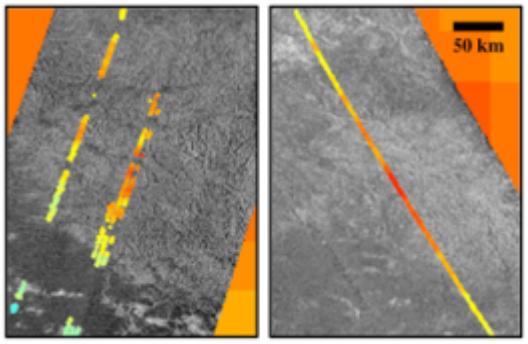

Figure 2: Cassini SAR images of the mountains at location A, flyby T59 (left) and location D, T07 (right). SARTopo data (points) and the base layer of the global interpolated topography are colorized with warm and cool colors to indicate high and low topography.

Finite Element Modeling: To test buoyant support and the stability of roots, we use the commercially available MSC.Marc finite element package, which has been well vetted in the study of the lithospheres of icy satellites [e.g. 5, 6]. The viscoelastic evolution of the mountains from locations A and D are investigated using axisymmetric meshes 5x as wide and 3x as deep

as half the mountain width. The initial mountain shape is 600 m or 1 km in height. We assume a Gaussian curve shape for the mountain and the isostatically balanced root, where we define the half-width (100 km for A and 175 km for D) as the radius where the Gaussian falls to 5% its peak height. The water ice shell is ostensibly 100 km thick with a density of 950 kg/m^3, and the ocean below has a density of 1,050 kg/m^3. We run three thermal simulations with different thermal structures: (1) a heat flow, q, of 4 mW/m^2, which is estimated to be the current heat flow on Titan [7] and translates to a temperature at the base of the ice shell T_b of 176 K (i.e., assumes ammonia antifreeze is present), (2) q = 6.6 mW/m^2 and T_b = 260 K (heat flow required to have a ocean without antifreeze at a depth of ~100 km), and (3) an extreme heat flow for comparison of 10 mW/m^2, with no basal temperature held. All simulations use the current surface temperature of 94 K. Additionally, we run simulations of all ice (no ocean) to determine the effects of buoyancy support. We pipe the results of a thermal simulation into the mechanical simulation, applying a water ice rheology that includes grain boundary sliding, diffusion creep, and dislocation creep for a grain size of 1 mm. Each simulation is run for a simulated time of 3 Gyr.

Preliminary Results: For all three heat flows, surface topography of the mountain is unstable and readily sags, decreasing the mountain height over time. The isostatic root flows away to a negligible size but much faster than the surface topography in every simulation (e.g., Fig. 3), primarily because the root's buoyancy cannot be adequately transferred to the surface, which thus is governed by the slower evolution of the lithosphere. We also find that there is very little difference between the simulations with mountains on an all-ice mesh and those with ice and an ocean layer in isostatic equilibrium for location A, and about a 100 m initial difference between them for location D. This finding confirms that the isostatic root is not transferring buoyant support to the surface topography over long periods of time.

Discussion: Our results indicate that mountain plateaus of this scale on Titan cannot be supported by Airy isostasy. The corollary is that these plateaus cannot be formed by crustal thickening; the buoyancy of a thickened crust will not transfer to, and therefore lift, the surface. To build these plateaus would require either a lower density material than the surrounding region (i.e., Pratt isostasy), or the mountain load was placed on top of the lithosphere. Both ideas could result from cryovolcanic processes: injection of clean ice into a dirty ice shell or eruption onto the surface. Consequently, we visually inspect the radar imagery at both locations for morphological signs of cryovolcanism. Location A did not show any obvious signs, aside from the fact that the feature is isolated and elevated

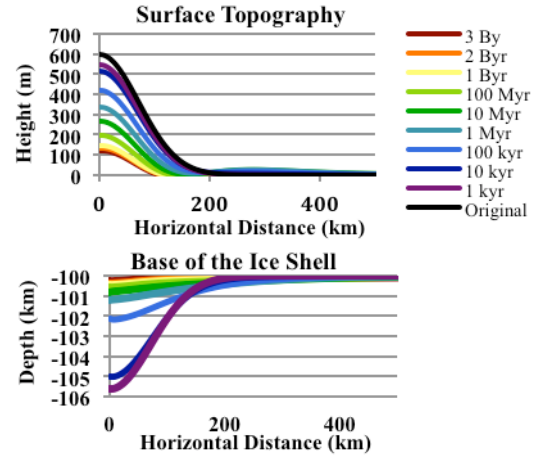

Figure 3: Finite-element simulation of the evolution of the mountain at location D with q = 6.6 mW/m^2.

above the surroundings and has morphologies consistent with being soft (pyroclastically deposited?), having badlands-style erosion (Fig. 2). Similar textures are present at location D, which also appears to have a large, flow-like feature emanating from a circular feature, possibly a caldera, near the summit (Fig. 4). We interpret this as a cryovolcanic rather than fluvial channel because the flow is significantly deeper than surrounding fluvial channels and originates from a single source that later fans outwards downslope, instead of acute-angle tributaries that are indicative of precipitation and rivers. This morphological evidence along with our modeling suggests a possibly cryovolcanic origin. Cryovolcanic features on Titan have been long searched for and debated [i.e., 8], and our study may have identified a new type of cryovolcanic feature on Titan, possibly analogous to shield volcanoes on the terrestrial planets.

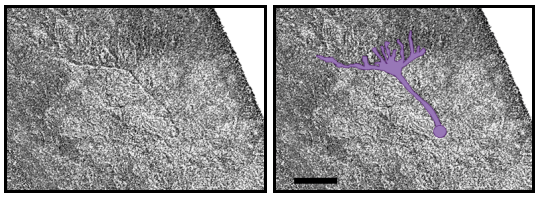

Figure 4: Possible cryovolcanic "caldera" and flow at location D. The scale bar is 25 km wide.

References: [1] Radebaugh, J. et al. (2007) *Icarus*, 192 77- 91. [2] Lorenz R. D. et al. (2013) *Icarus 225,* 367-377. [3] Karimi, M. and Dombard, A. J. (2011) AGU Abstract # PD43D-1712. [4] Stiles et al. (2009) *Icarus* 202, 584-598. [5] Dombard, A. J. and McKinnon, W. B. (2006) JGR, 111, E01001. [6] Schurmeier, L. R. and Dombard, A. J. (2015) LPSC Abstract # 2913. [7] Sohl, F. et al. (2003) *JGR*, 108, E12 [8] Lopes, R. M. C. et al. (2013) JGR, 118 416-435.