CRATER RELAXATION CAUSED BY AN INSULATING METHANE CLATHRATE CRUST ON TITAN. L. R. Schurmeier[1], G. E. Brouwer[1], S. A. Fagents[1], J. P. Kay[2], A. G. Marusiak[3], S. D. Vance[3] [1]Hawai'i Institute of Geophysics and Planetology, University of Hawai'i at Mānoa, Honolulu, Hawai'i, 96822, (lschurme@hawaii.edu), [2]Old Dominion University, [3]Jet Propulsion Laboratory, California Institute of Technology.

Introduction: Impact craters on Saturn's moon Titan are anomalously shallow, noticeably fewer in overall count than expected, and curiously absent in the polar regions [1-3]. Only 90 impact crater candidates have been identified, of which only 12 have been assigned the highest certainty of impact origin [3]. The crater distribution is not uniform: 65% of the craters are in the equatorial region, and there are 10% less than expected in the poles [3]. The craters with topographic data are hundreds of meters shallower than would be expected for the moon's size and assumed water ice composition [3]. Visually, many of the craters appear to be surrounded and commonly filled by sand, and are heavily modified (**Fig. 1**).

The shallowness of Titan's craters has been previously attributed to fluvial erosion from liquid from rain [2,3], aeolian sand infill [3], or topographic relaxation induced by insulating sand infill [4]. Here, we propose an additional mechanism: topographic relaxation due to the presence of an insulating methane clathrate hydrate crustal layer in Titan's upper ice shell.

Methane clathrate is a form of water ice that contains methane gas within the ice lattice cages. Clathrates could have formed in Titan's upper primordial crust, at the early ocean–core interface where it then rose to the surface, or via reactions of ice with liquid hydrocarbons [5-8]. Relative to ice Ih, methane clathrate is stronger [9] and denser, and has a significantly lower thermal conductivity [10]. We aim to test if a methane clathrate crust could warm Titan's ice shell and relax craters to their current depths.

Methods: We model the viscoelastic evolution of impact craters using Hexagon Marc, a finite element modeling (FEM) package used extensively to simulate lithospheric deformation (e.g., [4]). The initial depth is calculated from the depth-to-diameter ratio of fresh Ganymede craters [11]. We assume that the rim height is 30% of the depth and the shape is approximated by polynomials [4]. We model three diameters representative of Titan's craters: 100, 85 and 40 km.

Thermal profiles of Titan's interior are generated for crustal methane clathrate thicknesses of 5, 10, 15 and 20 km using the software PlanetProfile [12,13] which incorporates thermodynamic properties computed by SeaFreeze [14] and the numerical results of [15]. In our thermal FEM simulation, we divide the mesh into two layers (methane clathrate above water ice) and use the output from PlanetProfile to set the material properties and boundary conditions. We then import the thermal results into a mechanical simulation where we track the evolution of the impact crater morphology. In the axisymmetric mesh, a free-slip boundary is applied to the sides and the base is locked vertically and horizontally. We use a Maxwell viscoelastic rheology in each layer. For the elastic response, we use the properties of water ice from [16] and the ductile creep flow laws of [17] for ice and use [9] for clathrates.

Preliminary Results: The presence of crustal methane clathrate strongly affects the thermal structure of the crust. To maintain Titan's current expected ice shell thickness, thinner crustal clathrate layers result in higher crustal heat flows than thicker layers (i.e. 10 km clathrate = 7 mW/m^2, 15 km = 5 mW/m^2, 20 km = 4 mW/m^2). Thin crustal clathrates warm the ice shell which encourages ductile deformation and results in significant topographic relaxation (**Fig. 2**) compared to a pure ice shell [4].

To compare the simulated crater shapes with the observed crater topography, we compute a relative crater depth, R(D), defined as $R(D) = 1 - (d_s(D)/d_i(D))$, where $d_s(D)$ is the depth at specified simulated times and $d_i(D)$ is the initial unrelaxed depth. We find that any thickness of clathrate crust can result in the topographic relaxation of large craters, and a 5 km clathrate layer can relax the 40 km crater to some degree. We find that most of the relaxation occurs early on (<5 Myr, **Fig. 2**).

Discussion: The relative depth of Forseti, Hano, Afekan, Selk, and Sinlap could be achieved with a clathrate crust and enough time, without requiring fluvial erosion or sand infill (**Fig. 3**). Clathrate crusts 5-10 km thick result in the greatest relaxation, nearly removing the largest craters, except for their rims and a ring in the crater bowl that has not fully flexed upwards. This may explain Soi crater's current morphology (**Fig. 1B**). The absence of strong evidence of upbowed centers—a signature of extreme relaxation [1-3]— may be because the topographic measurements rarely pass through crater centers. If sand infill or mass transport by fluvial erosion are also occurring (e.g., crater #24W, **Fig. 1E**), those processes together could potentially reproduce the current shallow depth of all observed craters. Multiple mechanisms acting together could essentially remove large and medium size craters completely by filling craters at a fast rate, smoothing or hiding relaxed upbowed floors, and eroding the rims beyond recognition in SAR imagery. We conclude that methane clathrate crusts could be one cause of Titan's notably shallow craters, the biased crater distribution, and the overall sparsity of Titan's craters.

Acknowledgments: We thank Prof. A. Dombard for his assistance. This work is primarily funded by the NASA Cassini Data Analysis Program project "The Influence of Clathrates on Titan's Ice Shell" (Award No. 80NSSC22K0309) and partially funded by the NAI project "Habitability of Hydrocarbon Worlds: Titan and Beyond" (Award No. 17-NAI18_2-0017).

References: [1] Wood, et al. (2010) *Icarus*, 206. [2] Neish, et al. (2013) *Icarus*, 223. [3] Hedgepeth et al. *Icarus*, 344, (2020). [4] Schurmeier & Dombard, *Icarus*, 205, (2018). [5] Tobie et al. *Nature*, (2006). [6] Lunine & Stevenson, *Icarus* 70, (1987). [7] Loveday et al. *Nature* 410, (2001) [8] Vu et al. *GRL*, 47 (2020). [9] Durham, et al. *JGR*, 108, (2003). [10] Sloan & Koh, *Clathrate Hydrates of Natural Gases*. CRC Press, (2007). [11] Schenk, *Nature*, 417 (2002). [12] Vance et al. *JGR-Planets*, 123, (2018). [13] Marusiak et al., *PSJ*, 3, (2022). [14] Journaux, et al., *EPSEC-DPS*, 13, (2019). [15] Kalousová & Sotin, *GRL*, 47 (2020). [16] Gammon et al. *J Phys. Chem*. 87, (1983). [17] Goldsby & Kohlstedt, *J Geophys Res.*, 106, (2001).

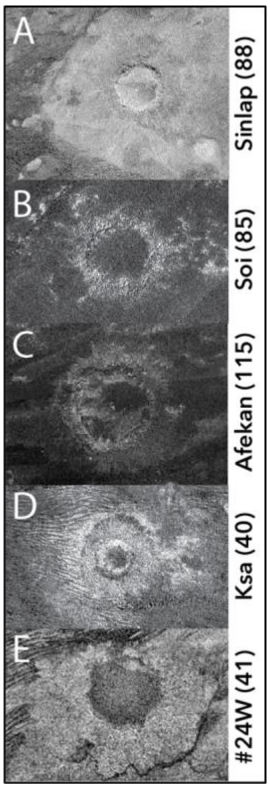

Figure 1: *Cassini* SAR images of some of Titan's impact craters (diameters in km, from [3]).

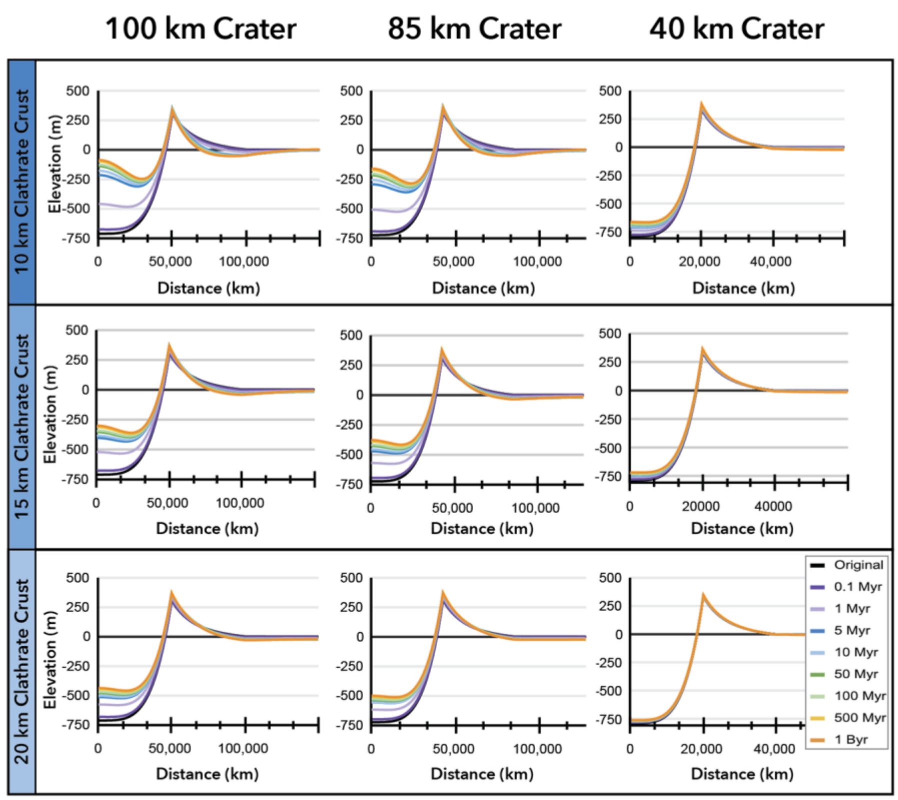

Figure 2: Relaxation of impact crater topography over time for crater diameters of 100, 85, and 40 km (columns), crustal methane clathrate crust thicknesses of 10, 15 and 20 km (rows), and a ice grain size 1 mm. Half of the crater is depicted.

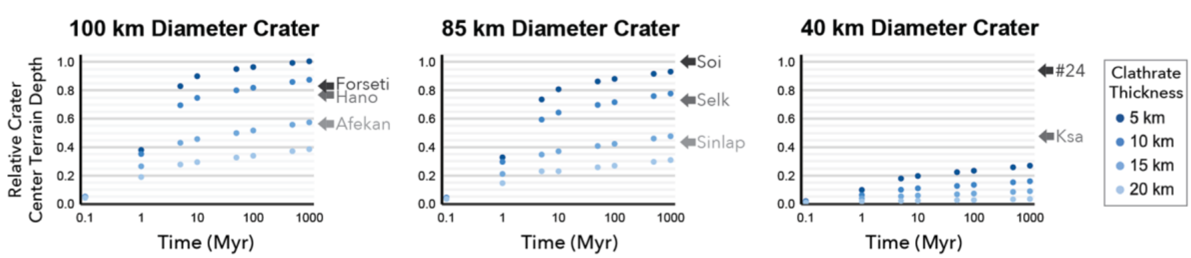

Figure 3: Relative crater depth of impact craters over time for three crater sizes. Here, relative depth is defined as the depth below the background terrain level at the center of the crater. Arrows indicate the current relative terrain depth of impact craters on Titan, which is often not centered due sparse topography data.