POSSIBLE IMPACT CONDITIONS FOR THE FORMATION OF SELK CRATER ON TITAN. S. Wakita[1,2*], B. C. Johnson[2,3], J. M. Soderblom[1], J. Shah[4], and C. D. Neish[4], [1]Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, USA, [2]Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, West Lafayette, IN, USA, [3]Department of Physics and Astronomy, Purdue University, West Lafayette, IN, USA, [4]Department of Earth Sciences, The University of Western Ontario, London, ON, Canada ([*]shigeru@mit.edu).

Introduction: Cassini observations revealed several impact craters on Titan [1], including Selk crater. This is an ~80 km diameter, ~0.5 km deep crater that has been selected as the landing region for NASA's Dragonfly mission [2, 3]. This region is of particular interest for the mission, as the formation of Selk crater should have produced melt pools of liquid water that could have been mixed with organics that are present on the surface. While VIMS spectra [4] and RADAR microwave emissivity [5] have provided some constraints about the composition and morphology of this region, detailed modeling is still needed to estimate the original extent of the melt deposit and the original depth of ejecta and their potential of melting. Here we simulate impacts into Titan and find that an ~4 km diameter impactor hitting a warm methane clathrate crust produces a crater similar to the size of Selk; these results will allow us to study the distribution of melt and subsequent aqueous processing of organic material by the formation of Selk.

Methods: We simulate crater forming impacts on Titan using the iSALE-2D shock physics code [6, 7, 8]. Methane clathrate, which is expected to form at Titan's surface [9], is stronger than water ice [10], and thus can influence the cratering process. In our simulations, we consider a methane-clathrate layer on top of a water-ice basement and use the strength model for methane clathrate from [11]. Although the surface temperature of Titan is known to be ~94 K, the temperature profile in the ice crust is less-well constrained. Because methane clathrate has a lower thermal conductivity than that of water ice [12], a methane-clathrate layer at Titan's surface will result in a higher temperature gradient, with the details depending on the thickness of the methane-clathrate layer [9]. In this initial work, we consider methane-clathrate layers of 5, 10, and 15 km, with the corresponding temperature profiles as shown in [9]. Note that the total ice-layer thickness is ~60 km. A steeper temperature profile, which allows warmer ice to exist close to the surface of the target, can generate a shallower and wider crater than a lower thermal gradient [13]. Our previous work showed that a 5 km diameter impactor into a cold methane clathrate layer produces an ~80 km diameter crater that is ~4 km deep, regardless of the methane clathrate thickness [11]. Here, we consider 3 to 4 km diameter icy impactors with an impact velocity of 10.5 km/s, an average impact velocity into Titan [14]. For all icy materials, we use the ANEOS equation of state for water ice. We use a simulation resolution of 50 m.

Results: Figure 1 illustrates the temperature profiles of the target after the 4 km diameter impactors strike the surface. For the case of the 5 km thick methane clathrate layer (Fig. 1A), the crater floor is dominated by warm water ice. When the temperature of the icy materials increases, its strength decreases and it moves more readily. Thus, the warm water ice moves upward (see white dotted lines in Fig. 1). We can see similar water-ice uplifts in the 10 km (Fig. 1B) and 15 km thick methane clathrate cases (Fig. 1C), though in the latter, the water-ice basement does not breach the methane-clathrate crust.

When there is a high central uplift of warm ice, it may push material over the rim during collapse; the overflow can obscure the rim [15]. If we observe such overflow, we define the crater diameter at the time of rim formation (well before this material overflows the rim). In the cases where there is no overflow, we determine the diameter at the end of crater formation simulation. We determine the rim height at the same time that we determine the crater diameter, and determine the depth as the vertical distance between the rim height and the lowest location in the crater floor at the end of the simulation. Figure 2 summarizes the diameter and depth of impact craters for different impactor sizes and methane-clathrate layer thicknesses. The crater formed by a 4 km diameter impactor in a 10 km thick methane clathrate layer has a 90 km diameter with a 1 km depth (green square in Fig. 2). It is wider than Selk crater, but similar in depth. The 3 km and 3.5 km impactors into a target with a 10-km thick clathrate layer also form ~ 1 km deep craters, with diameters of 65 km (green triangle) and 79 km (green circle), respectively. While a 4 km diameter impactor on a 15 km thick methane clathrate also produces a similar size crater (92 km wide and 1.1 km deep, blue square in

Fig. 2), craters formed by 3 km and 3.5 km diameter impactors into a target topped with a 15 km clathrate layer are deeper (blue triangle and circle in Fig. 2). This is because the smaller impactors cannot trigger the water ice uplift as in the 4 km impactor case (see Fig. 1C). Our results suggest that an ~4 km diameter impactor into a methane clathrate layer of 10–15 km thick with a higher temperature gradient is likely to form a Selk-like crater.

Discussions: Our impact simulations show that a few km diameter impactor into a methane clathrate layer over a water-ice basement can produce a crater that is similar in diameter to Selk crater. Although the crater depth on the warm methane clathrate is shallower than the cold case [11], it is still slightly deeper than Selk. This slight difference, however, may be explained by fluvial erosion and/or aeolian infilling [1, 16, 17] that can make Titan's craters shallower.

Our simulations can help to constrain the location and volume of the melt pool and the source of ejecta (the methane clathrate crust vs. the water-ice). As the uplifted warm water ice makes the crater shallower, it can have experienced melting. Thus, the shallower crater might have a large melt pool. It also can breach the methane clathrate crust and be ejected. Care must be taken to consider the effects of Titan's thick atmosphere, which can reduce the travel distance of the ejected material [18]. The ejecta is expected to be distributed and deposited nearer to the impact crater than is the case for impacts on airless bodies. Our further analysis might be useful for the Dragonfly mission.

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References: [1] Hedgepeth, J. E. et al. (2020) *Icarus,* **344**, 113664. [2] Lorenz, R. D. et al. (2021) *Planet. Sci. J.*, **2**, 24. [3] Barnes, J. W. et al. (2021) *Planet. Sci. J.*, **2**, 130. [4] Soderblom et al. (2010) *Icarus*, **208**, 905. [5] Janssen et al. (2016) *Icarus*, **270**, 443. [6] Amsden, A. et al. (1980) *LANL Report*, **LA-8095**, 101. [7] Collins, G. S. et al. (2004). *Meteoritics & Planet. Sci.*, **39**, 217. [8] Wünnemann, K. et al. (2006). *Icarus*, **180**, 514. [9] Kalousova, K., and Sotin, C. (2020) *GRL*, **47**, e2020GL087481. [10] Durham, W. B. et al. (2003) JGR, **108**, 2182. [11] Wakita, S. et al. (2021) 52nd LPSC #1173. [12] Sloan, E. D. J. et al. (2007) *Clathrate hydrates of natural gases* (CRC Press.). [13] Bjonnes, E. E et al. (2018) 49th LPSC #1548. [14] Zahnle, K. et al. (2003) *Icarus*, **163**, 263. [15] Silber, E. and B. C. Johnson (2017) *JGR*, **122**, 2685. [16] Neish, C. D. et al. (2013) *Icarus*, **223**, 82. [17] Neish, C. D. et al. (2016) *Icarus*, **270**, 114. [18] Carlson, M. C. et al. (2021) 52nd LPSC #1170.

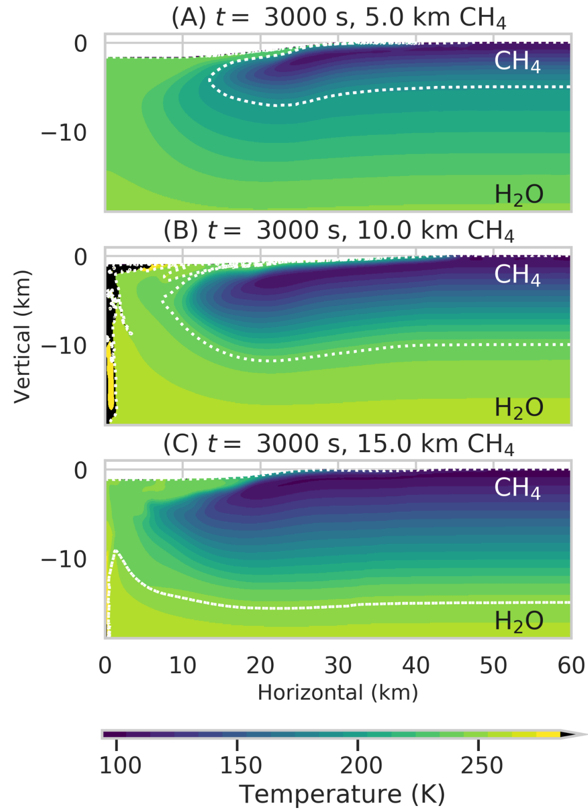

Figure 1. Temperature profile at 3000 s after the impact by 4-km-diameter impactors. Panels illustrate methane clathrate layers of (A) 5 km, (B) 10 km, and (C) 15 km. The white line represents the clathrate–water-ice material boundary.

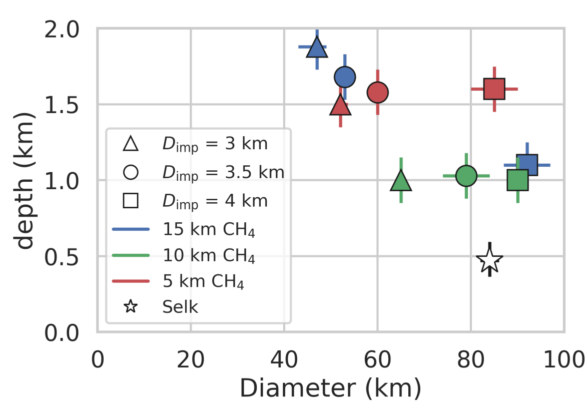

Figure 2. Crater depth versus diameter for impactors of different sizes (symbols) and methane-clathrate layer thickness (colors). The star symbol depicts Selk crater.