FROM LANDSLIDES TO THOLI: CERES' DIVERSE GEOMORPHOLOGY AND ITS IMPLICATIONS FOR GROUND-ICE. K. D. Duarte[1] , B. E. Schmidt[1], H. G. Sizemore[2], J. E. C. Scully[3], K. H. G. Hughson[4], P. M. Schenk[5], V. Romero[1], H. T. Chilton[1], A. Nathues[6], J. C. Castillo-Rogez[3], C. A. Raymond[3], C. T. Russell[4], and the Dawn Science Team. [1]Georgia Tech (kduarte3@gatech.edu), [2]Planetary Science Institute, [3]JPL/Caltech, [4]UCLA, [5]LPI/USRA, [6]Max-Planck-Institut für Sonnensystemforschung.

Introduction: Ceres is the largest body in the Main Asteroid Belt and was one of two objects explored by NASA's Dawn Mission. Infrared spectroscopy and gamma ray and neutron spectroscopy from Dawn confirmed as long suspected that Ceres contains water-ice on its surface [1,2] and within its subsurface [3]. The presence and morphology of different features on Ceres is also likely influenced by or formed from ice and ice-rock mixtures [4-6]. These features include landslides [4,6], ridges, fractures, and small domes [5]. The landslides were seen globally on Ceres, while the other proposed ground-ice related geologic features – mounds and fractures – were found within Occator crater. Using Dawn's Framing Camera (FC) imagery we mapped, classified, and quantitatively measured the array of geologic features seen on Ceres' surface.

Here we report on two facets of our ongoing analysis of surface features that are consistent with ice on Ceres. First, we report recent findings supporting the role of ground ice on a global scale in forming its landslides through analysis of the continuum of these features on Ceres. Second, we report new results from Dawn's second extended mission, XM2, regarding the distribution and properties of groups of small mounds or "tholi" within Occator crater that are candidate pingos. Finally, we discuss how these findings affect our growing understanding of the role of ice in forming Ceres landforms.

Lanslides: Landslides on Ceres exhibit an array of morphologies and appear in a wide range of geologic locations. They were originally classified into three main types based on their morphologies: Type 1 (T1), Type 2 (T2), and Type 3 (T3) [4]. T1 flows are lobate with prominent distal toes, and predominantly found above 70 degrees latitude. T2 landslides have long run-out lengths and are found across the globe, but generally occur below 70 degrees latitude. T3 flows resemble fluidized ejecta and are found at mid to low latitudes commonly within the ejecta of large impacts [4] [7]. The landslides' characteristics are hypothesized to be influenced by the concentration of ground-ice within the flowing material, and thus are an indication of the distribution of ice in any given region.

Intermediate landslides: While the original classifications of the T1, T2 and T3 landslides capture the behavior of a number of archetypal landslides, the majority of flows seen on Ceres do not fall cleanly within these three categories. Rather, these landslides fill a continuum of flow characteristics between the three types, and have been termed "intermediate" (IM) landslides [6]. Intermediate landslides have varying characteristics, including those presenting a combination of the original three types, as well as outlier traits specific to the individual flow. Additionally, IM landslides are seen all over the globe of Ceres and are not latitudinally limited, unlike T1 and T2 flows [6]. While IM landslides do appear to define a continuum of landslide characteristics, certain characteristics appeared more frequently. These include: occurrence at the contact point of the rim of an old crater and younger crater, multi-lobed features, landslides with distinct toes within fluidized ejecta, ponded material on crater walls, small landslides under 5km, and landslides not associated with craters [6].

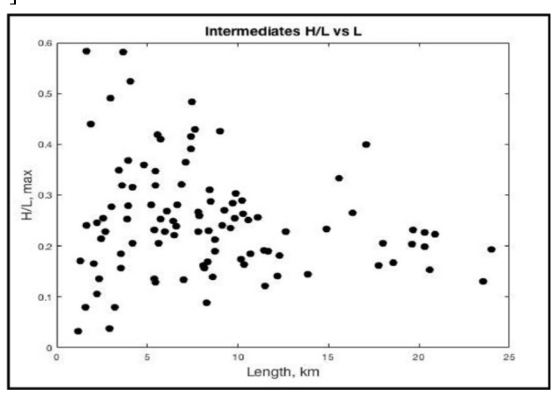

Figure 1: *H/L vs L compares an estimate of the potential energy to the eventual length of the flow. On Ceres, both the archetypal and intermediate flows demonstrate no clear relationship between H/L and L, which is consistent with high mobility [8] as argued in Schmidt et al (2017).*

Mechanical Behavior and Ice: An estimation of the mechanical behavior of the material that forms the landslide deposit is quantified through height versus run-out length (H/L) ratios of the landslides, a common determinate of coefficient of friction ratios [4] [9]. Using this ratio, we are able to compare the H/L ratio of a particular flow to that of other landslides, those on other bodies, and to the coefficient of friction ratio of ice and other materials to determine if ground-ice may have played a role in the mobility of the landslide. Generally, ice-influenced landslides have relatively longer run out lengths when compared to their H/L values, which is thought to occur due to lubrication by ice. Duarte et al. (2018) expanded on and revised H/L ratios from Schmidt et al. (2017), revisiting the originally classified T1, T2, and T3 flows, but also included the IM landslides. These are summarized in Figure 1.

Tholi in Occator Crater: Another geologic feature is thought to indicate ground-ice, small mounds (tholi) in Occator crater. Occator is a large, relatively young (~20 Myr) crater with multiple lines of evidence for impact melt and volatiles [10]. Due to its young age, the features seen in Occator are still in pristine condition. During Dawn's XM2 phase, the Framing Camera achieved a resolution as low as 5 m/px, increasing the ability to explore volatile-dependent processes within Occator, as well as providing a deeper insight into how other large, but now degraded, craters may have appeared in the past. Using FC images, we were able to extend the original work in Sizemore et al (2018) by identifying new features that were too small to be resolved with the prime mission data. Some of the most prevalent features seen in Occator are mounds and domes at a variety of scales, most notably Occator's central dome that spans approximately 3km in diameter.

Avg Diameter (m)	Avg Height (m)	Depression at peak	Fractures nearby
212.5	24.8	21.9% yes	23.6% yes
-	-	60.2% no	72.2% no
-	-	16.4% maybe	0.42% maybe

Table 1. *Current average diameter (m), height (m), and percentages of tholi with depressions at their peak and association with fractures.*

We identified several types of mounds that are often seen in clusters on the crater floor. Each group of features has been identified on the basis of spatial relationship and specific morphological characteristics. Interestingly, both the small mounds and the central Occator dome show similar physical characteristics to pingos found on Earth and Mars. There is also a tenuous correlation between mounds and fractures in some areas of Occator, with mounds having fractures form around and through them, though it is still unclear if the fractures or mounds formed first. We summarize the morphological data in Table 1.

Conclusions: Using geomorphology, we find that ice strongly influences the behavior of Ceres' surface, which has important implication for how the surface has evolved.

Landslides: Results from the H/L vs. L values combined with latitudinal trends and morphology of IM landslides, lead us to hypothesize that ground-ice is strongly influencing their formation, consistent with the results for the archetype landslides. We also find that the IM landslides are generally also consistent with a layered ice rich subsurface [11]. These landslides help constrain ice abundance variations across Ceres, and argue that the region surrounding Juling, Kupalo, and Urvara craters may be enhanced in ground ice.

Ice-rich Mounds: We hypothesize that the small mounds in Occator were created in a similar manner to terrestrial pingos. Occator's small mounds show terrestrial pingo-like characteristics: they are usually between a few hundred meters to 2km in diameter and only span a few hundred meters in height (Table 1). Most interestingly, some mounds also exhibit depressions at their peaks, much like terrestrial pingos. Terrestrial pingos typically form depressions due to melting or ice loss due to seasonal heating, and while we do not expect late-stage melting of pingos on Ceres, devolatilization of ice near the surface could drive pit formation similar to that seen in volatile rich floor materials elsewhere on Ceres [12]. The presence of these depressions on the mounds thus may support the idea that ground-ice has a role in their formation. The occurrence of ridges around the small mounds has been noted, but is still being investigated.

Overall, investigating these geologic features supports the hypothesis that ground-ice plays a key role in the subsurface of Ceres. Combined with other indications for ice, this places Ceres in context as only the third body where ground ice processes are observed.

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