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A new model of crater degradation on Ceres involving ice sublimation

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Introduction: More than 3 years of exploration of Ceres by NASA's Dawn probe has revealed a partially differentiated dwarf planet [1] with an ice-rich crust whose surface shows signs of volatile-related activity [2] and very recent, if not active, cryovolcanism [3]. Dawn's image data have enabled the production of a global geological map of the dwarf planet [4], as well as a large number of geomorphological studies of craters [5, 6] and mass-wasting deposits [7], with the aim of better constraining the ice content of the crust. Although mentioned and partially mapped in these studies, one morphology, present on the hillslopes of a large number of craters, has been overlooked even though it has the potential to provide valuable information about the rheology of the crust: talus deposits. Here we systematically mapped the talus units over the entire surface of Ceres.

Datasets and methodology: We used the global image mosaics from the Dawn Framing Camera produced by the DLR as our basemap for mapping talus. The majority of the mapping used LAMO (35 m/pix) mosaic, filling in where necessary with the data from the HAMO (140 m/pix) mosaic [8]. We also took advantage of the mosaic produced from the images acquired during the extended LAMO phase at a resolution of 3 m/pix when available. We used a DTM of the entire planet produced from HAMO images using the

stereo photogrammetry methods [8] to produce a geodesic slope raster with a resolution of 140 m/pix and investigate the slope angle of the talus deposits.

We defined talus units as a slope morphology comprising both rocky outcrops at the top of the hillslope, overhanging a smooth scree slope, as shown on Figure 1. Variation in the albedo of the material constituting the scree highlight lineations following the line of steepest slope and lobate margins of the deposits. Well-preserved talus have a sharp angle at the top of the slope, between the outcrops/scree and the ejecta blanket. They can also display a small bulge at the bottom of the scree slope, delimitating it from the crater floor. There is a continuum of talus morphologies. Talus features were then classified within 3 classes (talus type 1, 2 and 3) to take these morphological differences into account. Type 1 talus units are the best preserved ones and display all the morphological characteristics described before. Type 2 talus units have a less clear boundary at the bottom of the scree slope and a few superposed craters. Lastly, type 3 talus units have no sharp angle at the top of the slope, no clear boundary at the bottom and their scree is sprinkled with superposed craters.

Results: We mapped 324 talus units on Ceres distributed on the walls of 180 craters. Talus units occupy more than 2% of the available hillslope area on the walls of the craters. Hence they are the most common mass-wasting morphology known on Ceres. While type 3 talus units are the most numerous, they have the smallest median area per unit and have very few rocky outcrops. In contrast, type 1 talus deposits are few in number but have a median surface area per feature 6 times higher than type 3 talus. Also type 1 talus have a higher number of rocky outcrops per square kilometer. We assumed that these differences are related to the degree of degradation of the talus units.

Distribution of talus units on Ceres. We plotted the location of each mapped talus on the global map of Ceres and investigated their distribution. We saw no clear trend of the talus distribution with latitude and we did not observe any change in the talus morphology with increasing latitude. However, we noted that some craters (Occator, Ninsar, Kupalo, Juling and Dantu) have a very strong influence on the distribution, as they host a large area of talus deposits.

Radial distribution trend within the craters. We also examined the radial distribution of the talus deposits and rocky outcrops within their host-craters, separately

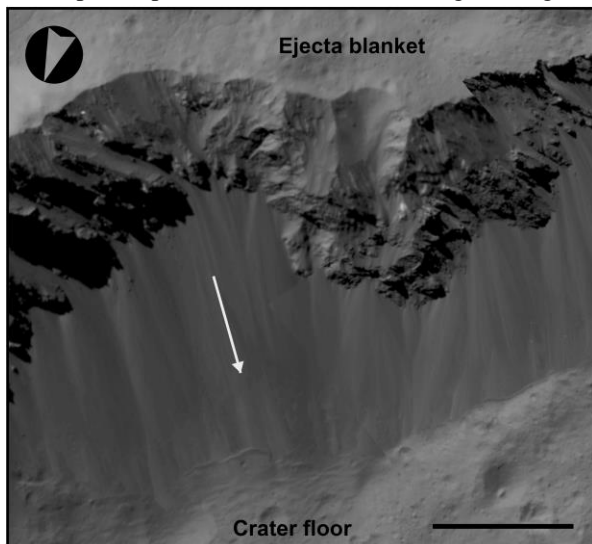


Figure 1. Mosaic of Dawn images of a T1 talus on the southern rim of Occator crater on Ceres. We observe a sharp angle at the top of the talus unit, and a small bulge at the bottom. Downslope direction is shown with a white arrow. Scale bar is 1 km long.

for both hemispheres. The talus area frequency radial distribution shows a slight increase on the pole facing walls. The same trend is much clearer for the frequency distribution of the outcrops. More than 75% of them are located on pole facing hillslopes in both hemispheres (Figure 2). This radial asymmetry within the craters is also observed when we measured the slope angle of the talus deposits as pole facing talus show slightly steeper slopes (around 5° steeper) than those facing equatorward.

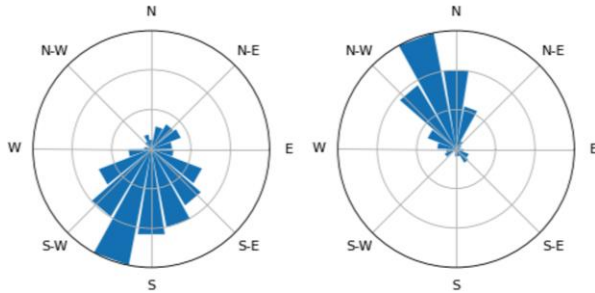


Figure 2. Radial distribution of rocky outcrops within their host-crater for northern (left) and southern (right) hemispheres.

Discussion: The asymmetric distribution of the talus deposits and rocky outcrops with more features, coupled with increased slope angle on the pole-facing walls of the craters suggest the involvement of volatiles in these morphologies. In Juling crater, previous spectral analysis of one of the biggest outcrops on Ceres revealed the presence of water ice [9]. Moreover, other studies have suggested that boulders which have fallen from the outcrops in Urvara crater also harbor ice. [10]. Hence, we extrapolate that most outcrops are ice-rich and we suggest that the slow sublimation of the ice they contain is responsible for their loss of cohesion and the subsequent fall of the dry regolith material forming scree slopes. This process would be widespread on Ceres as we observe talus everywhere. The different talus preservation states suggest that it is an ongoing active process at the surface of Ceres. The formation of scree due to ice sublimation within the outcrops is also consistent with the increasing surface area of talus on pole facing walls as the rate of the headwall degradation and retreat depends on the illumination conditions. Also, the greater slope angle of the pole facing hillslopes can be explained by the greater number of outcrops on these slopes, leading to a higher mean value of the slope angle.

Conclusion: The observation of widespread talus deposits within craters of various sizes and with different preservation states across Ceres led us to propose a new scenario of crater degradation, as illustrated on Figure 3. Whereas for an atmosphere-free body like

Ceres, we might have expected the predominant impact crater degradation process to be topographic diffusion due to impact and spatial weathering [11], we highlight a new crater evolution process directly linked to the rheology of the cerean crust. We assume that the ice-rich cohesive regolith exposed by impacts would slowly sublimate leading to the slow retreat of the wall and the formation of scree slopes. The formations of talus units likely depends on the illumination conditions and would be slower on the pole facing walls, leading to a longer activity of the talus units that would allow for a longer preservation. Compared to topographic diffusive processes, the retreat of the wall due to talus formation leads to an increase in crater diameter with time. This could have an influence for crater counting on Ceres. All of this could also suggest that the superficial crust of Ceres could be made of a fine granular regolith whose cohesion is ensured by cementing ice.

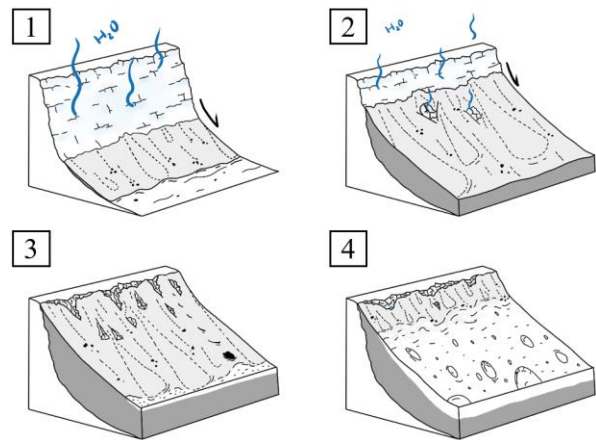


Figure 3. Crater hillslope evolution scenario involving talus formation (1 and 2) and degradation (3 and 4), driven by cementing-ice sublimation.

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