A GLOBAL INVENTORY OF ICE-RELATED MORPHOLOGICAL FEATURES ON DWARF PLANET CERES.

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Introduction: Data sets collected by Dawn during its primary mission at Ceres have confirmed the presence of substantial subsurface ice, and revealed a more complex distribution of ice than was previously predicted [*1–3*]. Understanding the burial depth, concentration, and mobility of subsurface ice on inner solar system worlds is of great interest from the standpoints of cosmoschemistry, astrobiology, and future in situ resource utilization.

The inventory of ice in localized surface exposures on Ceres has been quantified by the Visible and Infra-Red Mapping Spectrometer (VIR-MS) [*4*]. The ice content of the uppermost meter of Ceres' regolith is well characterized by data from Dawn's Gamma Ray and Neutron Detector (GRaND) [*3*] and by thermal stability simulations [*5*]. The ice content of the deep interior (length scales of 10s of km) is constrained by gravity and global topography data [*2*, *6*]. At intermediate depth ranges (10s of meters to kilometers), analysis of surface morphology has been critical to investigating the concentration of ice and other volatiles [*1*, *7–9*]. Here, we present a new comprehensive catalog of morphological features relevant to the presence and concentration of subsurface ice and other volatiles, along with updated global maps of features that have been previously studied. We discuss the implications for local and regional variations in subsurface ice content.

Methods: We carried out iterative global searches for features of interest in Framing Camera (FC) images and mosaics during each of Dawn's mapping orbits at Ceres, beginning with Rotational Characterization 3 (RC3; 1.3 km/px), and continuing through Survey (410 m/px), High Altitude Mapping Orbit (HAMO; 140 m/px), and Low Altitude Mapping Orbit (LAMO; 35 m/px). As each global data set became available it was searched independently, then features identified in previous, lower resolution data sets were re-evaluated and interpreted based on the highest resolution images, digital terrain models (DTMs), and numerical modeling, as appropriate. Our final catalog and maps include both (1) features for which there is substantial evidence that ice played a key role in landscape develop-

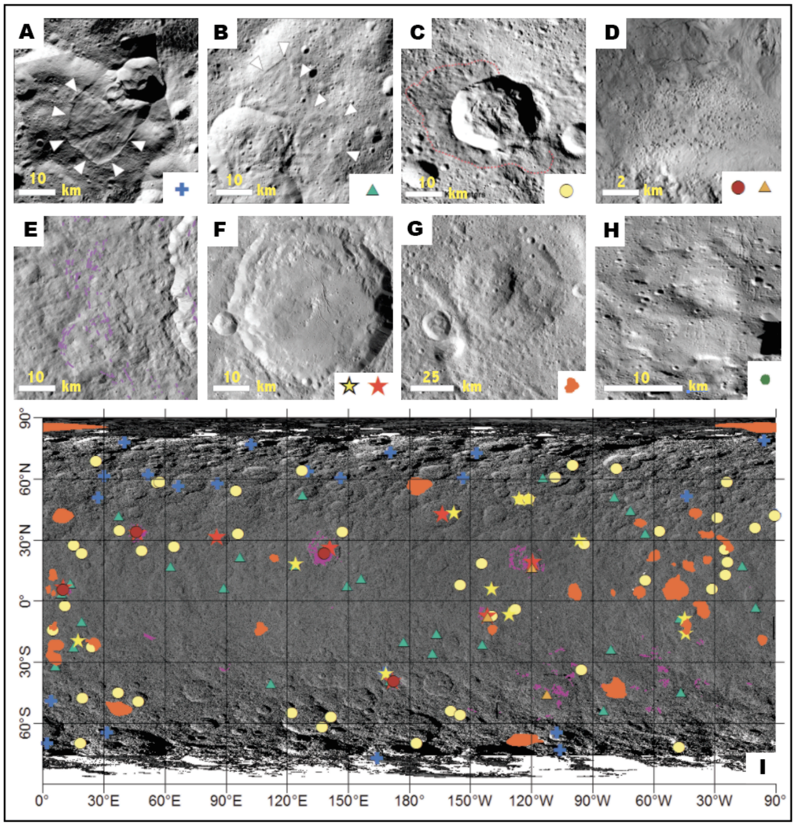

Figure 1. Overview of morphological features related to subsurface ice on Ceres. Examples of type 1 (A) and type 2 (B) landslides, fluidized or lobate ejecta (C), pitted materials (D), circumferential fractures (E), crater floor fractures (F), large domes (G), and small mounds (H) are shown in the upper panels, along with their respective map symbols. Panel I shows the global distribution of these features.

ment, and (2) features for which there is a circumstantial case for ice or volatile involvement and which merit further scrutiny in the event of a future Ceres mission.

Results: We identified six broad classes of features with clear or potential relevance to ground ice: *landslides and ejecta* (types 1–3, Fig. 1 a–c), *pitted materials* (Fig. 1 d), *depressions and scarps* (not pictured), *large domes* (Fig. 1 g), *small mounds* (Fig. 1 h), and *fractures, grooves and channels* (Fig. 1 e–f).

Landslides and lobate ejecta were some of the first features recognized on Ceres to have relevance to ice [*8*, *10*]. Analysis of Ceres' layered ejecta (feature type 3) is consistent with a crustal composition of < 29 vol.% carbonates, <25 vol. % water ice, and > 36 vol. % high strength hydrated phases (plus 10 vol. % void space) [*11*]. Latitudinal variations in landslide morphology (feature types 1 and 2) are suggestive of latitudinal variations in temperature and possibly the concentration of ground ice in the upper kilometers of Ceres' crust [*12*].

Pitted materials are likely produced by the rapid outgassing of volatiles from heated ejecta and are observed only at mid and low latitudes on Ceres. Analysis suggests H_2O is the dominant gas species, and is sourced from ice and hydrated mineral phases. Occurrence of these features is likely consistent with < 50 vol. % ice in the ejecta layer (~100s m) [*9*]. A small number of irregular *depressions and scarps* are not clearly linked to ice or volatiles, but have been retained in the catalog due to their proximity and common setting with pitted materials, and their morphological similarity to features produced by ice sublimation elsewhere in the solar system.

A variety of *large domes* (10s of km in diameter, km high) were evident in the earliest RC3 images of Ceres [*10*]. We identified 33 of these features globally. One, Ahuna Mons, has been interpreted to be a young cryovolcanic construct [*13*], and the others have been hypothesized to be similar, viscously relaxed constructs [*14*] or evidence of solid state ice diapirism [*15*]. The preferential occurrence of these features in ancient basins and their morphology support cryomagmatic and/or cryovolcanic origin. *Small mounds* (<1–5 km in diameter, 100s of m high) are a diverse group of features that have potential relevance to small-scale cryovolcanism or pingo development [*16*, *17*], but interpretation of these features is limited by image resolution.

Fractures, grooves, and channels is an umbrella feature class that includes three distinctive subgroups of features that commonly occur together and grade into one another at some locations. *Floor fracture craters* (FFCs; Fig. 1 F) are craters with distinctive large-scale floor fractures and/or circumferential moats, hypothesized to develop as the result of cryomagmatic intrusion beneath the crater by analogy with the Moon [*10*, *18*]. *Circumferential fractures* in smooth ejecta external to crater rims may result from the relaxation of a crater on top of a soft subsurface layer. The ductile behavior of such a layer may be generated by a relatively high abundance of buried ice [*19*]. Small-scale *grooves and channels* in the smooth floor materials of large impact craters have been suggested to result from mobilization of volatiles in the heated ejecta layer [*20*].

Discussion: Broadly, the distribution of morphological features linked to ice is consistent with inferences from neutron spectroscopy, and gravity and topography analysis, which indicate that the dwarf planet's crust (outer ~50 km) is comprised of a mixture of phyllosilicates and carbonates, ice, and hydrated salts and/or clathrates. The global distribution of our mapped features suggest that subsurface ice is present globally on Ceres, that silicates and high strength water bearing phases (hydrated salts, clathrates) are the volumetrically dominant regolith material in the crust. Further, the asymmetry of fluidized and lobate ejecta deposits and the geographic clustering of some features – especially potential cryomagmatic or cryovolcanic features – suggests that there are substantial vertical and lateral heterogeneities in the volume fraction of ice at a variety of length scales. The Cerean cryosphere and its unique morphology and composition promise to be a rich subject of ongoing research.

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References: [1] M. T. Bland *et al.* (2016) *Nat. Geo.*, **9**, 538. [2] R. R. Fu *et al.* (2017) *Earth & Plan. Sci. Let.*[3] T. H. Prettyman *et al.* (2017) *Science*, **355**, 55. [4] J.-P. Combe *et al.* (2017) *Icarus*. [5] N. Schorghofer (2016) *Icarus*, **276**, 88. [6] A. I. Ermakov *et al.* (2017) *JGR-Planets*. [7] P. Schenk *et al.* (2015) *EPSC*. [8] B. E. Schmidt *et al.* (2017) *Nat. Geo.*, **10**, 338. [9] H. G. Sizemore *et al.* (2017) *GRL*. [10] D. L. Buczkowski *et al.* (2016) *Science*, **353**, aaf4332. [11] K. H. G. Hughson, E. al. (2017) *AGU Fall Meeting*. [12] H. T. Chilton, *et al.* (2017) *48th LPSC*. [13] O. Ruesch *et al.* (2016) *Science*, **353**, aaf4286. [14] M. M. Sori, E. al. (2018) *49th LPSC*. [15] M. T. Bland, E. al. (2018) *49th LPSC*. [16] O. Ruesch, E. al. (2017) *48th LPSC*. [17] L. C. Quick, E. al. (2018) *49th LPSC*. [18] D. L. Buczkowski, E. al. (2018) *49th LPSC*. [19] K. Otto, E. al. (2018) *49th LPSC*. [20] D. A. Crown *et al.* (2017) *Icarus*.