CERES' PITTED TERRAINS: MORPHOLOGICAL CONTEXT AND IMPLICATIONS FOR GROUND ICE.
H. G. Sizemore[1], T. Platz[1,2], N. Schorghofer[3], D. A. Crown[1], T. H. Prettyman[1], M. C. De Sanctis[4], D. L. Buczkowski[5], K. H. G. Hughson[6], S. Marchi[7], S. C. Mest[1], D. A. Williams[8], P. M. Schenk[9], M. T. Bland[10], B. E. Schmidt[11], H. T. Chilton[11], C. T. Russell[6], C. A. Raymond[12], and the Dawn Science Team. [1]Planetary Science Institute, Tucson AZ, USA (sizemore@psi.edu), [2]MPI for Solar System Research, Göttingen, Germany, [3]University of Hawai'i, Honalulu, HI, USA, [4]Istituto di Astrofisica e Planetologia Spaziali, INAF, Rome, Italy, [5]JHU-APL, Laurel, MD, USA, [6]University of California Los Angeles, Los Angeles, CA, USA, [7]Southwest Research Institute, Boulder, CO, USA, [8]Arizona State University, Tempe, AZ, USA, [9]Lunar and Planetary Institute, Houston, TX, USA, [10]USGS Astrogeology, Flagstaff AZ, USA, [11]Georgia Institute of Technology, Atlanta, GA, USA, [12]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA.

Introduction: Prior to the arrival of the Dawn spacecraft at Ceres it was anticipated that the dwarf planet's outer shell might be water ice rich [e.g., 1]. Using Dawn Framing Camera (FC) images, we have carried out global searches for morphological features that are potentially diagnostic of the presence of sub-surface ice based on analogies with a variety of solar system objects [e.g., 2, 3].

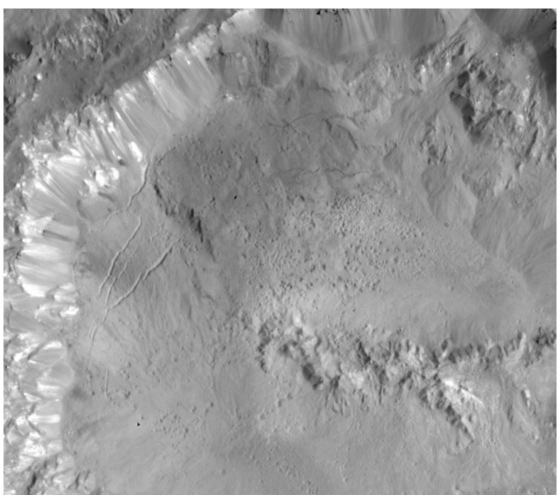

Fig. 1. Pit clusters, flows, and fractures on the floor of Haulani crater.

We have identified distinct pitted terrains in the FC Low Altitude Mapping Orbit (LAMO) dataset (35 m/px). We describe the morphology, setting, and geographic distribution of these terrains, which exhibit striking similarities to pitted materials previously discovered by Dawn at Vesta [4], and to pitted materials identified in low-and mid-latitude martian craters [5]. We discuss spatial relationships between pitted terrains and other morphological features of interest on Ceres, including fluidized and lobate ejecta, lobate mass wasting features [2, 6], crater floor fractures [7], and small scale grooves and channels [8]. Finally, we evaluate the likely role of ice and other volatiles in the development of pits.

Methodology: Because Ceres' surface morphology is dominated by impact structures, distinguishing between features produced by volatile loss (sublimation, outgassing) and features produced by small impacts was an ongoing consideration in our analysis of FC data. Our criteria for identification of pits, depressions, and pit clusters relevant to volatiles were the presence of (1) rimless depressions, or depressions with subtle rims that do not rise above the surrounding terrain [5], (2) individual pits or depressions with round-to-irregular or polygonal margins, and (3) overlapping or repeating patterns. Concurrent with our search for pits and depressions, we mapped and catalogued other morphological features with potential relevance to volatiles, noting spatial correlations.

Following completion of our global feature searches, we investigated possible mechanisms of pit development, using morphological comparisons to other solar system bodies and established numerical models of near-surface volatile transport [9, 10].

Results: All of the rimless pits identified in our global search were associated with pristine and well preserved impact craters. Extensive pits occur in and around Dantu, Ikapati, Haulani, and Kupalo craters. More muted depressions identified in less-well-preserved Urvara and Azacca craters likely represent degraded pit clusters. Pit clusters are rare in Occator, which hosts two larger unique depressions [11].

Pit morphology. Individual pits are negative relief features that appear quasi-circular to polygonal in plan form, and typically occur in tightly overlapping clusters incised in smooth crater floor materials and in ponded ejecta. Pits exhibit a range of depths within individual clusters and are generally conical or fluted in profile, rather than flat-floored. Pit size varies based on (1) size of the host crater, (2) proximity to the crater center and (3) thickness of the host deposit. In general, the largest pits occur in the crater fill deposit, often where smooth crater floor materials form a quasi-equipotential surface. Successively smaller pits occur in smooth material ponded on wall terraces and in the continuous ejecta blanket. At Dantu (diameter 126 km) and Ikapati (diameter 50 km), pit diameters range from ~1km down to ~100 m, the limit of FC resolution (~35 m/px in Low Altitude Mapping Orbit or LAMO). Typical pit depths are 10s of meters on the Dantu and Ikapati floors; the largest pits are deeper than 150 m. At Kupalo (diameter 26 km) the largest pits are near the limits of FC resolution. Pits were not identified at Oxo (diameter 10 km) craters, although ice has been detected there [11].

Pit development. The morphology, setting, and size-distribution of cerean pits all bear striking similarities to pitted materials previously identified in pristine craters on Mars [5] and on Vesta [4], suggesting a common formation process. Boyce et al. [9] developed a model of martian pit development in which pit clusters form via the rapid escape of volatiles from a melt-bearing brecciated layer soon after impact. Application of this model to Vesta and Ceres indicates that the outgassing process is more efficient in the asteroid belt, due to the low gravitational acceleration and lack of atmosphere [3]. H_2O from ground ice and hydrated minerals is assumed to be the dominant volatile responsible for pit formation on Mars [5,9]. On Vesta, pit forming H_2O is likely sourced from chondritic impactors [4], but an ice contribution cannot be ruled out [13]. Thus, a key question becomes: Is endogenic ground ice implicated in pit formation at Ceres?

The larger morphological context. The cerean craters that host pitted materials also exhibit several morphological characteristics that have been independently linked to modest quantities of ice. These include:

1. Fluidized & lobate ejecta, which has been cited as evidence for ground ice on Mars and Ceres [e.g., 6, 14, 15]. Cerean pit clusters are incised in smooth impact materials that form ponded equipotential surfaces and exhibit multiple indications of flow, including streamlining, diversion around obstacles, and (less frequently) toes or levees at a distal margins. The occurence of pits on flows in crater interiors and in ponds connected by "channelized flows" on continuous ejecta is directly analogous to the relationship between pits and flows observed on Mars [5] and distinct from Vesta, where evidence for flow is more limited and layered ejecta with lobate margins is not observed [16].

2. Small-scale grooves, fractures, and channels. Across Ceres, smooth impact materials associated with well-preserved craters are marked by small scale grooves or fractures. We observe these small-scale linear features at every location where we identified pits. On continuous ejecta blankets and in ponded material on wall terraces, small grooves and fractures are typically concentric to the source crater; however, the grooves sometimes divert and become concentric to topography underlying the smooth deposit. This diversion around underlying topography, particularly buried crater rims, is suggestive of fracturing due to drape folding of a volatile rich layer, and possible enhancement of fractures by sublimation or outgassing [17]. Interior to the source crater, grooves can form complex networks on floor deposits, often intersecting with or linking to larger, deeper floor fractures (see below). Similar grooves and fractures are associated with martian pitted crater materials [5]. Networks of grooves in Urvara and Yalode floor material also grade to small-scale channels, interpreted to form via localized flow in a volatile-bearing ejecta deposit [8].

3. Crater Floor Fractures. Every crater in which we have identified pitted materials hosts large-scale radial or concentric fractures in its floor materials. The pitted craters are the most well-preserved members of a larger group of craters that have been independently identified as analogous to Type I Floor-Fractured Craters (FFC) on the Moon [18]. Lunar FFCs have been linked to post-impact magmatic intrusion. A cryomagma is implicated if a similar process produces the cerean FFCs.

4. Simple-to-complex crater transition and depth-to-diamter ratios. The large-scale morphology of cerean craters is analogous to impact structures on icy satellites and distinct from Vesta. Depth-to-diameter ratios are also consistent with an ice-rich crust [19]. However, crater topography on Ceres persists over billion-year timescales, indicating that silicates dominate the crust volumetrically [20].

Discussion: Viewed in the larger context of crater morphology at Ceres, there is a strong circumstantial case that endogenic ground ice contributes to the development of pitted terrains on Ceres. We will present the morphological argument for ground ice involvement in the context of recent detections of water ice and hydrogen by VIR [12, 21] and GRaND [22] respectively. Further, we will place quantitative constraints on the volumetric abundance of ice in the upper km of Ceres' mid- and low-latitude regolith.

References: [1] McCord T. B. & Sotin C. (2005) *JGR, 110.* [2] Schmidt B. E. et al. (2017) *Nat. Geosci., in review.* [3] Sizemore H. G. et al. (2017) *Nat. Astron., in review*. [4] Denevi B. W. et al. (2012) *Science, 338,* 246-249. [5] Tornabene L. L. et al. (2012) *Icarus, 220,* 348-368. [6] Hughson K. H. G. et al. (2017) *48th LPSC.* [7] Buczkowski D. L. et al. (2017) *48th LPSC.* [8] Crown D. A. et al. (2017) *Icarus, in review.* [9] Boyce J. M. et al. (2012) *Icarus, 221,* 262-275. [10] Schorghofer N. (2016) *Icarus, 276,* 88-96. [11]Ruesch O. et al., *48th LPSC.* [12] Combe J.-P. et al. (2016) *Science, 353.* [13] Scully J. E. C. et al. (2015), *Earth & Plan. Sci. Let., 411,* 151-163. [14] Carr M. H. et al. (1977) *JGR, 82,* 4055-4065. [15] Chilton H. T. et al. (2017) *48th LPSC.* [16] Hughson, K. H. G. et al. (2015) *46th LPSC,* Abstract #2075. [17] Buczkowski D. L. & Cooke M. L. (2004) *JGR*, *109.* [18] Buczkowski D. L. et al. (2017) *48th LPSC.* [19] Hiesinger H. et al. (2016) *Science, 353*. [20] Bland M. T. et al. (2016) *Nat. Geosci.,* 9, 538-542. [21] De Sanctis M. C. et al. (2017) *48th LPSC.* [22] Prettyman T. H. et al. (2017) *Science,* 355, 55-59.