SPECTROSCOPY OF DOMES ON CERES AND IMPLICATIONS FOR EMPLACEMENT. Joel A. Wilner[1], Alexander J. Evans[1], Ralph E. Milliken[1], Michael M. Sori[2,3]. [1]Department of Earth, Environmental and Planetary Sciences, Brown University (joel_wilner@brown.edu); [2]University of Arizona; [3]Purdue University.

Introduction: The origin of several dozen enigmatic domes distributed across the surface of Ceres is the subject of considerable recent debate [1-5]. Ahuna Mons, the tallest of these domes, has commonly been linked to icy extrusive processes ("cryovolcanism"), owing mainly to its isolated presence and morphometric similarity to terrestrial lava domes [1, 2]. Since the discovery of Ahuna Mons, 32 other large domes (1–4 km tall, >10 km in diameter) have been identified [3, 6] and putatively linked to cryovolcanism by virtue of viscoelastic relaxation models of ice-rich edifices matching observed latitude-dependent dome aspect ratios [3]. However, a competing model has been shown to replicate domes of similar height through solid-state flow of low-viscosity, low-density (LVLD) subsurface material upon differential gravitational loading, a process analogous to terrestrial salt doming [4].

Although each hypothesis for the domes' formation offers compelling arguments, it remains to be known whether or not both processes act upon the surface of Ceres in tandem. Namely, spectroscopic properties of relevant domes have not yet been analyzed in a holistic manner that ascertains the likelihood of one emplacement process over the other. Although Ahuna Mons has been the subject of a detailed compositional study that inferred a higher abundance of Na-carbonates than its surroundings [7], these methods have not been applied to other domical constructs.

In this study we incorporate statistical analyses of visible and infrared spectroscopic data from the Dawn Visual and Infrared Imaging Spectrometer (VIR) instrument to (1) characterize the spectral features of domes on Ceres with respect to surrounding terrains and (2) consider implications for the cryovolcanism and solid-state flow hypotheses of dome emplacement.

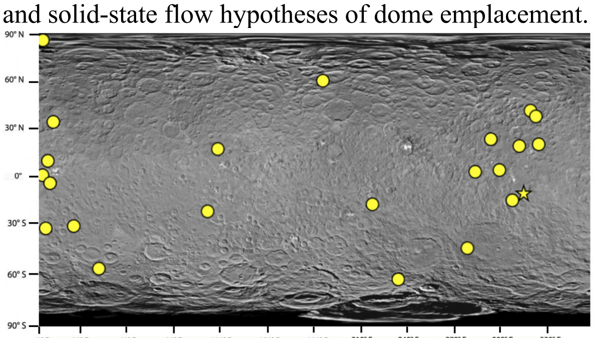

Fig. 1. Global distribution of 22 conservatively selected domes (circles; star indicates location of Ahuna Mons) on Ceres, over the global Framing Camera mosaic from Dawn. Figure adapted from [3].

Methods: We use radiometrically calibrated (level 1b) Dawn VIR image cubes from the HAMO (high-altitude mapping orbit) and LAMO (low-altitude mapping orbit) mission phases that encompass spectral radiance of 20 of the 22 domes conservatively selected by [3] and their environs (two domes are outside the observational range of VIR). A thermal correction is applied by fitting a black body curve to radiance between ~4.6 and 5.0 μm and subtracting its contribution from the spectra, according to the method of [8]. To convert to I/F (reflectance), we divide the spectral radiance values by the solar radiance spectrum, accounting for the appropriate Sun-Ceres distance at each observation.

Following the approach of [7] applied to Ahuna Mons, we examine key spectral parameters from the flanks and summit units of each dome, as well as from the surrounding terrain separate from the dome with the goal of quantifying how spectrally distinct each dome is relative to an assumed "typical" surface spectrum of Ceres. The first-order parameter we consider, and the focus of this abstract, is spectral slope. Though it can be influenced by a number of factors, spectral slope is a useful proxy for compositional variability and terrain maturity (e.g., degree of space weathering), and can be diagnostic of grain size [9]. The later may be useful for first-order inferences about dome emplacement mechanisms. Similar to the approach of [7], we compute spectral slopes between 0.55–0.85 μm and 1.00–1.90 μm via a best fit linear trend through I/F for a given wavelength range. Spectral parameter maps are mapped in an equirectangular projection using photometric cubes created in the ISIS3 software.

Statistics: Non-dome spectra are averaged from pixels within an annulus of maximum radius ~25 km around each dome. Normalized for albedo, the variance is computed for spectral parameters of interest. Spectral parameter values for the summit and flank pixels are compared against the variance of non-dome annulus pixels. The "distinctiveness" of spectral slopes and individual band depths is quantified by calculating the variance of the dome pixels from the annulus spectral slope means and band depth means, respectively.

Future work: Additional analyses being performed include band depth and temperature analyses. Computing the depths of bands associated with minerals of interest, namely Na- and Mg-carbonates and hydrated minerals, is a priority. In the assumption of uniform grain size, band depths can be used to infer relative abundance of the mineral of interest; in the assumption of uniform composition, band depth can yield information about grain size. In either case, valuable information is obtained about the degree of distinction of the domes from surrounding terrains. The inherent temperature of the dome regolith will be inferred through the correction for surface temperature and compared with solar incidence angle; this attribute can provide information about the compactness of dome material that can be further used as evidence for dome distinction. Spectral distinction parameters are compared against inferred dome age from [3] to investigate any possible correlations with composition, grain size, or compactness and emplacement age.

Spectral Slopes: Here, spectral slopes in the visible and near-IR wavelength ranges are presented as a preliminary proxy for terrain maturity and spectral distinction of domes. Figure 2 shows results for the three youngest domes, each less than 300 Ma as estimated by [3].

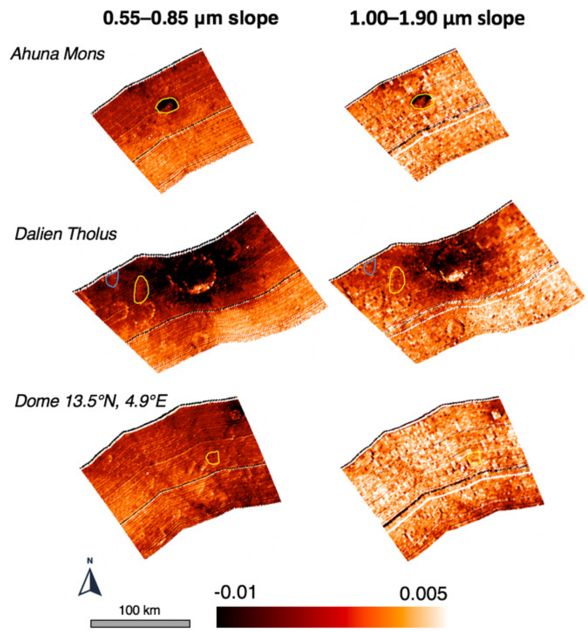

Fig. 2. Spectral slopes in the visible and near-IR derived from HAMO data for the three youngest domes considered in this study. Yellow lines mark locations of domes.

As in [7], we find significantly smaller spectral slopes values for the flanks of Ahuna Mons compared with its surroundings in both the visible and near-IR (Fig. 2), possibly indicative of coarser regolith and/or a younger age than its surroundings. Unlike Ahuna Mons, Dalien Tholus (as well as the unnamed tholus immediately to its northwest, marked by a blue line) shows an increased spectral slope in the visible wavelengths, which might point to a finer regolith and/or an older age than its surroundings, but similar slope to its surroundings in the near-IR. In contrast, the unnamed dome at 13.5°N, 4.9°E does not exhibit any distinction in spectral slope from its surroundings. These preliminary results suggest that domes on Ceres may be spectrally diverse which could point to a range of emplacement mechanisms if these variations are in fact related to surface composition and grain size. Subsequent work as part of this study, namely the inclusion of additional spectral parameters such as band depths for the complete group of domes, will help to constrain the extent of this diversity and will determine whether or not there exists a relationship between spectral characteristics and dome age.

Implications for Formation Mechanisms: It is difficult to use any particular outcome to exclusively diagnose a cryovolcanic origin or a solid-state flow origin. Although it stands to reason that a cryovolcanic dome might be more spectrally distinct from its surroundings than a solid-state flow dome because extrusion introduces a large quantity of new material to the surface whereas a solid-state flow dome would likely raise the existing surface from underground without disrupting the surface, these outcomes should not be considered exclusive. Instead, it is more useful to consider what the spectroscopic observations mean for either dome-forming scenario (Table 1). Our future mineralogical analyses will help to distinguish between emplacement mechanisms.

<table>
<tr><th rowspan="2">Dome-forming scenario</th><th colspan="3">Spectrally distinct from surroundings?</th></tr>
<tr><th rowspan="3">Yes</th><th colspan="2">No</th></tr>
<tr><td rowspan="2">Cryovolcanism</td><td colspan="2">Dome < 600 Ma?</td></tr>
<tr><td>Yes</td><td>No</td></tr>
<tr><td></td><td>Cryolava compositionally and/or texturally distinct from host terrain</td><td>Cryolava compositionally indistinct from host terrain</td><td>Cryolava likely buried by impact ejecta</td></tr>
<tr><td>Solid-state flow</td><td>LVLD material exposed at surface</td><td>LVLD material confined to subsurface</td><td>LVLD material confined to subsurface or buried by impact ejecta</td></tr>
</table>

Table 1. Possible spectroscopic outcomes given different dome-forming scenarios. Impact ejecta burial timescale is based on twice the 50% probability of burial timescale for Ceres since 2.5 Ga from [10].

Acknowledgments: Data were acquired from the PDS Small Bodies Node.

References: [1] Ruesch O. et al. (2016) *Science*, *353*; [2] Sori M. M. et al. (2017) *GRL, 44*, 1243-1250. [3] Sori M. M. et al. (2018) *Nat. Astrom*., *2*, 946-950. [4] Bland M. T. et al. (2019) *Nat. Geosci*., *12*, 797-801. [5] Ruesch O. et al. (2019) *Nat. Geosci*., *12*, 505-509. [6] Buczkowski D. L. et al. (2016) *Science*, *353*. [7] Zambon F. et al. (2017) *GRL*, *44*, 97-104. [8] Kaplan H. H. et al. (2018) *GRL*, *45*, 5274-5282. [9] Clark R. N. (1999) *Remote Sensing for the Earth Sciences–Manual of Remote Sensing, vol. 3*. [10] Stein N. et al. (2017) *Icarus*, *320*, 188-201.