**IMPACT CRATERING ON THE SMALL PLANETS CERES AND VESTA: S-C TRANSITIONS, CENTRAL PITS AND THE ORIGIN OF BRIGHT SPOTS.**

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**Introduction:** Dawn global high-resolution mapping of Ceres at ~35 m and Vesta at 20-m pixel scales reveals a rich variety of well-preserved impact crater morphologies on the two large asteroids. The mixed-ice-rock composition of Ceres and similar surface gravity with Vesta and the mid-sized icy satellites provides a unique opportunity to compare crater morphologies in different target compositions under similar conditions. Pre-arrival studies predicted that Ceres impact craters might resemble those on the midsize icy moons of Saturn (of similar size and density to Ceres) if Ceres had an ice-rich interior. Revised global shape and spectral data [1] now point to a mixed ice-rock outer shell in which water ice is likely no more than 30% by volume.

**Impact Morphologies from Peaks to Pits:** Morphologies of Cerean complex craters are surprisingly similar to icy satellites (Fig. 1). Craters between 7.5 and ~40 km on Ceres and on Tethys and Dione have steep rimwalls and wide floors covered by irregular mounds and arcuate to concentric ridges and scarps (the latter similar to Rheasilvia on Vesta [2]!). Central peaks become apparent in such craters at D>20 km, as they do on icy moons. Debris flows are also visible along rimwalls. Boulders are common on the rims and floors of fresh complex craters, consistent with formation of abundant secondary craters in craters > ~50 km on Ceres and at a few craters on Vesta, and at ~1D from crater rims.

The transition to complex craters begins ~6-8+/-2.5 km diameter on Ceres, depending on the measure, consistent with those of Tethys and Dione using the same criteria on all bodies [2]. Fresh crater depth/ diameter ratios are also indistinguishable from those on ice-rich Dione and Tethys [2]. The transition does not occur until >30 km on Vesta (Fig. 2).

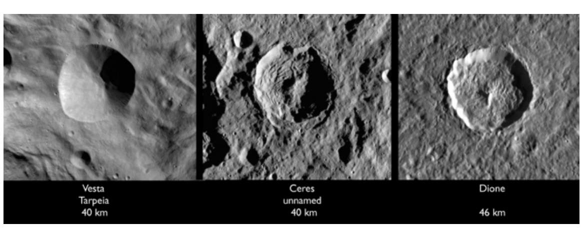


Figure 1. Comparison of similar sized craters on Vesta, Ceres, and icy moon Dione.

At D>40 km, however, Cerean craters begin to include floor-fill materials, something never seen in the Saturn system. These form discrete units at different topographic levels within the crater, sometimes perched among terraces, or low-lying areas in the ejecta, etc. These materials are very flat at 1-km scales, but are very rugged at <100 m scales forming irregular textures of knobs, sinuous ridges, lobate flow margins, etc. Floor fractures are also common in these larger craters. These units and their distributions are similar to those of Copernicus and Tycho, but are not observed on Vesta, even in the largest impact basin, Rheasilvia [3], consistent with the lack of melt on a dry silicate asteroid [4]. The similarity in mean impact velocities requires Ceres be composed of materials easier to melt than Vesta, possibly consistent with warm ice in the outer layers (pending updated calculations and experiments).

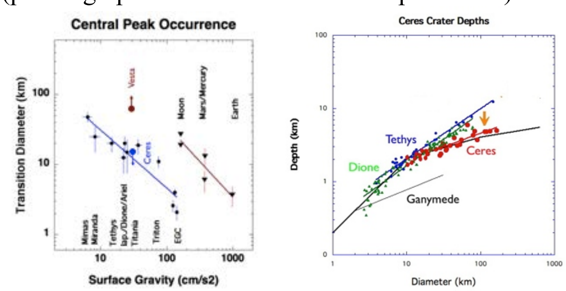


Figure 2. Central peak transition diameters (left) and d/D relations for Ceres (right), based on Survey mapping data.

Despite the lack of central pits on Saturn's icy moons, central pit craters are prevalent on Ceres at >75 km diameters (Fig. 3), consistent with gravity scaling from the larger Galilean satellites. Pit dimensions (~0.15$D$) are similar to those on Ganymede, and exhibit both peak-pit and floor-pit morphologies similar to those on Mars and on Ganymede/Callisto [5]. The lack of pits on Saturn icy moons may be related to low internal temperatures or paucity of non-ice materials.

**Occator: Type Example of a Fresh Impact Crater & the Formation of Bright Spots:** Bright spot crater Occator (D~90 km) is relatively pristine large crater on Ceres. Rim terraces, floor fractures and continuous ejecta are well preserved. A rugged but flat-lying deposit interpreted as an impact melt sheet partially covers the floor. Crater densities across Occator floor and ejecta appear to be highly variable, suggesting possible influence from self-secondaries [6], though material strength and late-stage surface modification may contribute.

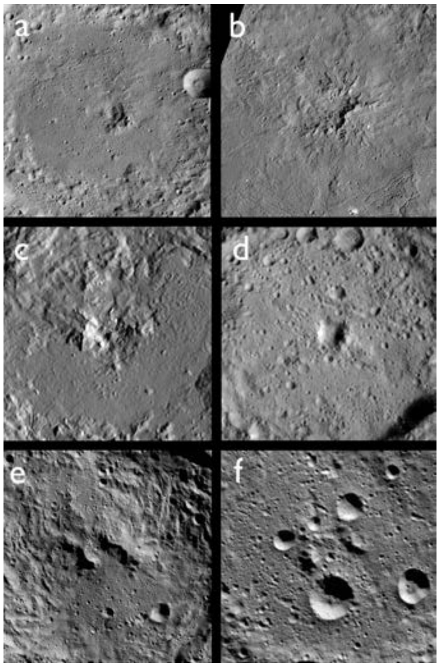


Figure 3. Dawn LAMO images centered on typical central pits on Ceres. Pit widths are ~10-20 km.

The largest bright spot is associated with the 9-km-wide central depression, or pit. A 3-km-wide 750-m high central dome (similar to those on Ganymede/Callisto) occupies the floor of the pit [2] (Fig. 4). The dome is fractured, as are those on Ganymede/Callisto and has a distinct color and perhaps a different composition where exposed in the fractures [7].

The association of prominent bright spots with the central structure suggests that either uplift or localized extraction or extrusion of compositionally distinct material is involved in bright spot formation in the most strongly uplifted zones of large craters on Ceres. At small-scales, bright materials across Occator are concentrated in local lows and are 'blocked' by scarps or knobs, forming sinuous ribbons and discrete small spots. Whether material extruded from multiple vents, and in a liquid or gaseous or solid state remains to be determined, but topographic control could be consistent with hydrothermal models [8] whereby hot fluids flow on the surface short distances, evaporating and precipitating salts, carbonates or other materials out in low-lying areas.

Floor and outer rim fractures are generally concentric to the rim. Most cut "flat-floor" material on Occator floor, suggesting fracturing after emplacement, whereas others are cut by rim debris, suggesting rapid formation. Fracturing could be due to contraction (due to either simple cooling of a melt or dehydration of bound water due to residual impact heat in a hydrated or ammoniated silicate), to failed terrace formation, or to post-impact uplift (such as during viscous relaxation). The floor of Tycho is also heavily fractured, possibly to contraction cooling of the impact melt sheet or the crater floor itself, but it is not yet clear if the fractures on Ceres are formed by similar mechanisms as those on Tycho.

**Conclusions:** At D<40 km Cerean craters resemble those on midsize icy moons, including floor morphologies and transition D's, but at larger diameters have characteristics more similar to the larger Galilean satellites and the Moon, including terraces and floor deposits indicative of impact 'melt'. This contradiction with evidence for a stronger outer layer resistant to viscous relaxation [9] could be consistent with a mixed ice-rock outer layer if its rheologic behavior *during the impact process* is dominated by the weakest material (i.e., ice). Relatively weak non-ice materials (e.g. hydrated-silicates, salts) may also play a role.

All the observed features are simplest and best explained by regular impact processes, nuanced for Ceres conditions and composition. Flat-lying floor-fill material has morphologies consistent with impact melt on other bodies, and bright spots could be related to outgassing of hydrothermal-style fluids leading to residual surface deposits of salt or carbonate [10]. Post-impact deformation occurs in the form of fractures and bright deposit formation. The large lobate floor deposit could be post-impact deformation but the weight of evidence currently favors impact melt/mud. Crater morphologies on Ceres may be a reflection of the complex chemistry of the Cerean outer layers as a hybrid mixed body formed in the transition zone between the rocky inner planets and water-rich outer planets. Dawn XM2 results will also be discussed.

**References:** [1] Park, R. (2017) *Nature*, 537, 515-517; Fu, R, (2017) *EPSL*, 476, 153-164. [2] Schenk, P., et al. (2015) *EPSC* EPSC2015-400. [3] Schenk, P., et al., (2012) *Science*, 336, 687-689. [4] Keil, D. et al., (1997) *Met. Planet. Sci*. 32, 349. [5] Schenk, P., (2017) *Icarus,* in revision. [6] Zanetti, M. (2015) LPSC, abst. 1209. [7] Schroeder, S. (2015) AGU abstract. [8] Dombard, A., and P. Schenk, *DPS*, 2015. [9] Bland, M., et al., (2017) *Nature* Geosci., 9, 538-542. [11] Ammonnitto, E. et al. (2016) Science, 353, Doi: 10.1126/science.aaf4279.