IMPACT CRATERS ON CERES: PROBES OF NEAR-SURFACE STRUCTURE AND COMPOSITION

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Overview: NASA's Dawn spacecraft entered Ceres orbit in March of 2015 and has (to date) attained global imaging at resolutions as high as 410 m/pixel. In contrast to some pre-Dawn predictions [1], these images reveal a heavily cratered surface. The persistence of pristine crater morphologies over geologic time provides direct constraints on Ceres' near-surface composition and structure, and requires a relatively high-viscosity near-surface more consistent with a thick, frozen rock regolith (more rock than ice) than the relatively pure water ice shell suggested by theoretical interior models [2, 3]. Other more exotic compositions with high viscosity are also possible.

Basic crater morphology: In general, Ceres' impact craters have morphologies similar to those of the icy satellites in the outer Solar System (Fig. 1A). The simple-complex transition diameter is 10-15 km, consistent with impacts into low-strength material, and a number of central pits have been observed. Crater depths are similar to those on Dione and Tethys [4] (which have similar gravity). The substantial depth of Ceres' craters (100-km diameter basins can reach depths of ~4-6 km) contradicts pre-Dawn expectations [1].

Surprise! Ceres has deep craters: Impact craters are negative loads (uncompensated topography) that induce topographic stresses in the near surface of planets. If the viscosity of the near-surface is sufficiently low, the material will undergo solid-state flow that acts to remove the crater topography. Such "viscous relaxation" is observed on the icy satellites of both Jupiter [5,6] and Saturn [7,8] (Fig. 1B).

Based on its shape (which is consistent with a differentiated body in hydrostatic equilibrium [9]) and low density (2100 kg m^{-3}) [10], Ceres was thought to contain a near surface ice layer below its rock exterior [2, 3, 9]. However, the surface temperature of Ceres (~180 K at the equator) is sufficient for ice to flow over relatively short geologic timescales [1]. If Ceres' outer shell were pure ice (with a mechanically weak rocky surface lag), any 30-km diameter crater in the equatorial region older than 100 Ma should have a depth of ≤100 m (Fig 2A). A similarly aged 60-km diameter crater nearly anywhere on the body should be effectively flattened (Fig 2B). The timescales for viscous relaxation are extremely short (geologically) for a relatively pure ice layer.

How is crater topography retained on Ceres? To retain impact crater topography, the viscosity of Ceres' near-surface must be substantially higher than the viscosity of pure water ice. Mixing particulate material (rock or salts) into the ice increases the viscosity of the mixture by up to a factor of ~10x for volume fractions (ϕ) up to 50-60% [11,12,13]. Figure 3 shows the effect of increasing the viscosity of the ice by up to a factor of 10x (consistent with ϕ~50%) on the expected depth of a 1-Ga-old, 60-km diameter crater. The "dirty" ice does not prevent nearly complete relaxation unless the grain size of the ice is large. However, large grained ice and substantial particulate material are generally mutually exclusive, as the particulates pin grain boundaries and prevent the growth of large grains [14]. Dirty ice therefore cannot prevent Ceres' craters from relaxing.

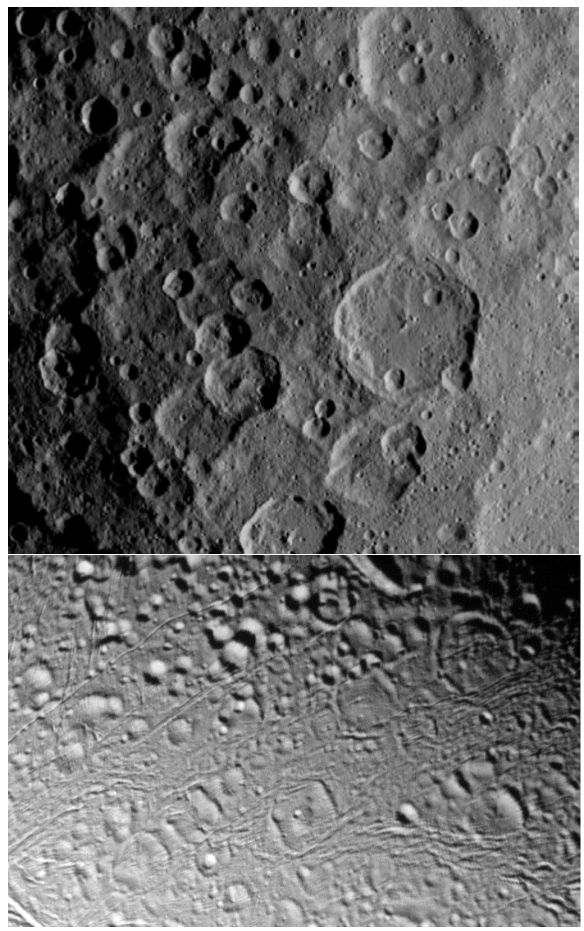

Figure 1: (Top) Typical impact craters on Ceres, which do not show obvious evidence for relaxation. Image is 450 km across. (Bottom) Viscously relaxed impact craters on Enceladus with flat or up-domed floors and intact rims. Image is ~170 km across.

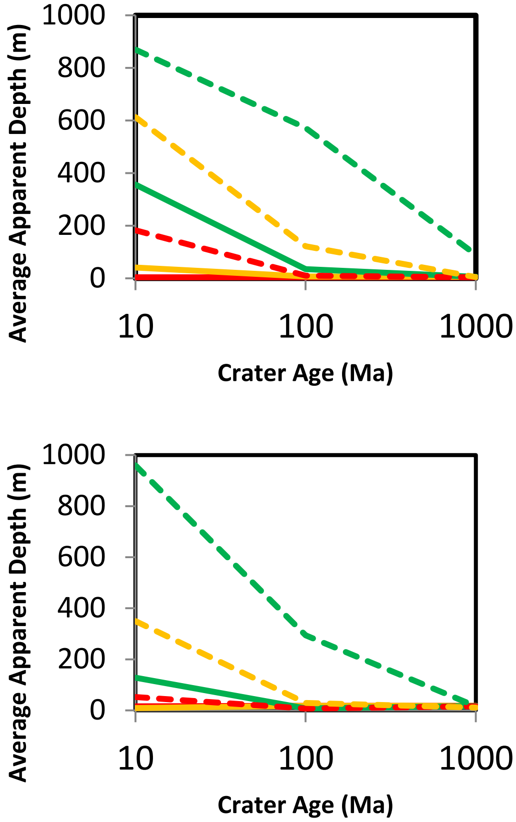

Figure 2: The expected depth of a 30-km-diameter (top) and a 60-km diameter (bottom) impact crater as a function of crater age assuming Ceres has a pure water ice shell with a grain size of 1 mm (solid curves) or 10 mm (dashed curves). Red, yellow, and green curves correspond to surface temperatures of 180 K (equatorial), 160 K (mid latitudes), and 140 K (polar), respectively.

An alternative possibility is that Ceres near-surface consists of a relatively thick "crust" composed of frozen regolith (i.e., more dirt than ice). Such a layer could have a viscosity substantially greater than pure water ice. Figure 4 shows the effects of such a layer on a 1-Ga-old, 60-km-diameter crater. Thin layers do not effect relaxation; however, once the layer thickness approaches the crater radius relaxation is inhibited and substantial crater depths (300-400 m) can be maintained.

Conclusions: Ceres' impact craters reveal the near-surface of the Dwarf-planet to be compositionally complex. The substantial topography observed is inconsistent with either pure or "dirty" water ice. Only rock-ice mixtures that are more-rock-than-ice are consistent with observations. We continue to consider more exotic compositions, such as layers of hydrated salts.

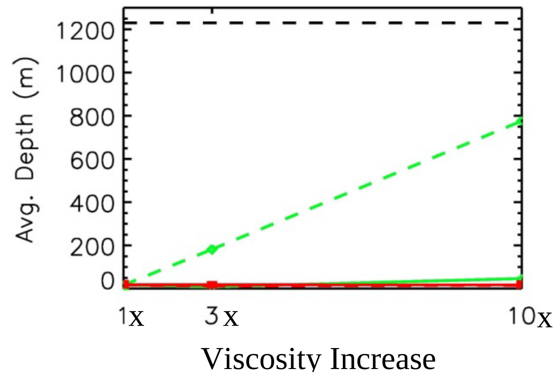

Figure 3: The average depth of a 1-Ga-old, 60-km diameter crater as a function of increasing viscosity due to particulate material (1x-10x pure ice). Values correspond to particulate volume fractions up to 60%. Curves are as in Fig. 2.

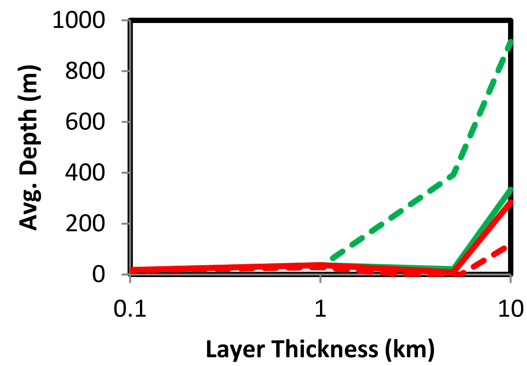

Figure 4: The effects of a high-viscosity surface layer (100x pure water ice) of variable thickness on the expected depth of a 1-Ga-old, 60-km-diameter crater. Curves are as in Fig. 2.

References: [1] Bland, M. T., 2013. *Icarus* 226, 510-521. [2] McCord, T. B. and Sotin, C., 2005. *JGR* 110, E05009. [3] Castillo-Rogez, J. and McCord, T. B., 2010. *Icarus* 205, 443-459. [4] Schenk, P. M. et al., 2015. *AGU Fall Meeting*, (pending). [5] Passey, Q. and Shoemaker, E. M. 1982. In: *Satellites of Jupiter*, 379-434. [6] Bland et al., 2011. *LPSC*, #1814. [7] Bland et al. 2012. *GRL* 39, L17204. [8] White et al. 2013. *Icarus* 223, 699-709. [9] Thomas, P. C. et al. 2005. *Nature* 437, 224-226. [10] Michalak, G. 2000. *Astron. Astrophys.* 360, 363-374. [11] Friedson, A. J. and Stevenson, D. J. 1983. *Icarus* 56, 1-14. [12] Durham, W. B. et al. 1992. *JGR* 97, 20883-20897. [13] McCarthy C. et al. 2011. *JGR* 116, E04007. [14] Barr, A. C and McKinnon, W. B. 2007. *JGR* 112, E02012.