

**THE HAMO-BASED GLOBAL GEOLOGIC MAP AND CHRONOSTRATIGRAPHY OF CERES.** S.C. Mest<sup>1</sup>, D.A. Crown<sup>1</sup>, R.A. Yingst<sup>1</sup>, D.C. Berman<sup>1</sup>, D.A. Williams<sup>2</sup>, D.L. Buczkowski<sup>3</sup>, J.E.C. Scully<sup>4</sup>, T. Platz<sup>1</sup>, H. Hiesinger<sup>6</sup>, J.H. Pasckert<sup>6</sup>, A. Neesemann<sup>7</sup>, S. Marchi<sup>8</sup>, R. Jaumann<sup>9</sup>, T. Roatsch<sup>9</sup>, F. Preusker<sup>9</sup>, A. Nathues<sup>5</sup>, C.A. Raymond<sup>4</sup>, C.T. Russell<sup>10</sup>, and the Dawn Science Team, <sup>1</sup>Planetary Science Institute, 1700 E. Ft. Lowell Rd., Suite 106, Tucson, AZ 85719 ([mest@psi.edu](mailto:mest@psi.edu)); <sup>2</sup>School of Earth & Space Exploration, ASU, Tempe, AZ; <sup>3</sup>JHU-APL, Laurel, MD; <sup>4</sup>NASA JPL, California Institute of Technology, Pasadena, CA; <sup>5</sup>MPI for Solar System Research, Göttingen, Germany; <sup>6</sup>Institute for Planetology, WWU, Münster, Germany; <sup>7</sup>Freie Universität, Berlin, Germany; <sup>8</sup>SwRI, Boulder, CO; <sup>9</sup>DLR, Berlin, Germany; <sup>10</sup>UCLA, Los Angeles, CA, USA.

**Introduction:** NASA's Dawn spacecraft arrived at Ceres on March 5, 2015 and has been studying the dwarf planet through a series of successively lower orbits, obtaining morphological, topographical, mineralogical, elemental, and gravity data [1]. The Dawn Science Team is conducting a geologic mapping campaign for Ceres similar to that done for Vesta [2,3], including production of an Approach- and Survey-based global geologic map [4] at 1:10M-scale, a High Altitude Mapping Orbit (HAMO)-based global geologic map [5] at 1:2.5M-scale, and a series of 15 Low Altitude Mapping Orbit (LAMO)-based 1:500K-scale quadrangle maps [6]. In this abstract we discuss current results from the HAMO-based global geologic mapping effort for Ceres.

**Mapping Methodology:** The HAMO-based global geologic map of Ceres (Figure 1) is being produced at a scale of 1:2.5M using ArcGIS (v. 10.3). The Dawn Framing Camera (FC) HAMO (~140 m/pixel) mosaic [7] serves as the primary basemap, and is supplemented by the global HAMO DTM (137 m/pixel) [8] and FC color mosaics (0.44-0.96  $\mu\text{m}$ ) [9]. These data are used to identify contacts and features, and for unit characterization. High-resolution LAMO images were used in limited cases where contacts were difficult to discern.

The geologic map displays contacts (accurate, approximate, and inferred symbologies) to delineate geologic units, point symbologies to identify important features (e.g., bright spots, small tholi, central peaks), and linear features to identify positive- and negative-relief structures and features that are linear to arcuate in planform (e.g., ridges, crater rims, scarps, grooves, crater chains, pit chains, troughs). Because of the map scale, only geologic units greater than 100 km<sup>2</sup> in area, impact craters greater than 20 km in diameter, and linear features longer than 20 km are shown on the map.

**Mapping Results:** Geologic mapping has defined widespread units – *cratered terrain*, *smooth material*, and units of the Urvara/Yalode system – as well as a series of widely distributed impact-related units (e.g., crater floor, terrace, central peak, rim, and ejecta materials). *Cratered terrain* forms most of Ceres' surface and exhibits rugged surfaces derived largely from the structures and deposits of impact features. The material of the cratered terrain includes the oldest terrains exposed on Ceres, but the geologic materials likely consist

of crustal materials heavily mixed with various impact materials. *Smooth material* forms nearly flat-lying to hummocky plains in the western equatorial hemisphere; this unit is found on the floor of, and surrounding, crater Kerwan, where it embays the cratered terrain. The geologic materials related to the Urvara and Yalode basins consist of impact materials (floor, rim, and ejecta deposits) that cover a large part of Ceres' eastern and southern hemispheres. Urvara ejecta consists of a rugged and a smooth facies, whereas Yalode ejecta can be distinguished by its smooth and rolling to stucco-like texture. Superposition relations show that ejecta deposits and structures from Urvara superpose Yalode.

Impact materials are mapped across Ceres, and include different *crater materials* and *crater floor materials* (e.g., *smooth*, *hummocky*, *bright*, and *dark*). Crater material is identified around many of the more fresh-appearing craters. These deposits include primarily rim and ejecta materials, as well as crater floors where floor materials can not be discerned as a separate unit. The ejecta deposits of some morphologically fresh craters, such as Haulani, Occator, Dantu, and Azacca, are associated with a blue to light blue color in the FC color mosaic that correlates with "rayed" patterns [10,11].

Impact craters are the most prevalent features on the surface of Ceres, and appear to have caused most of the visible geologic modification of the surface [12]. Craters exhibit sizes ranging from the limits of resolution to the large structures of Urvara (170 km), Yalode (260 km), and Kerwan (284 km). Craters appear morphologically "fresh" to moderately degraded, with rims that are nearly circular and raised above the surrounding terrain. Small fresh craters (<15 km) display simple bowl shapes, whereas larger fresh craters display steep walls and flat (sometimes fractured) floors [4]. Many craters exhibit irregularly shaped, sometimes scalloped, rim structures, and many of these craters contain hummocky deposits, some with lobate edges, on their floors.

**Chronostratigraphy:** The goal of developing the chronostratigraphy of Ceres is to organize the major geologic events or stratigraphically significant geologic units that are separated in time into distinct time-stratigraphic systems. The chronostratigraphy of Ceres is based primarily on (a) relative ages determined from stratigraphic relations (superposition, cross-cutting, em-

bayment) observed in the HAMO mapping process, supported by (b) absolute model ages (AMAs) determined from calculating crater size-frequency distribution (CSFD) statistics of the HAMO-based map units using craters identified and measured on LAMO images. Through mapping and stratigraphic analyses we have identified distinct geologically significant events and units to be used as candidate stratigraphic referents that define four major systems: pre-Kerwanan, Kerwanan, Yalodean, and Azaccan. We present our current version of the chronostratigraphy for Ceres (Figure 2), but note that it is still under development. Preliminary boundary ages are shown using a lunar-derived model only, and the referents could change following additional Dawn science team discussions.

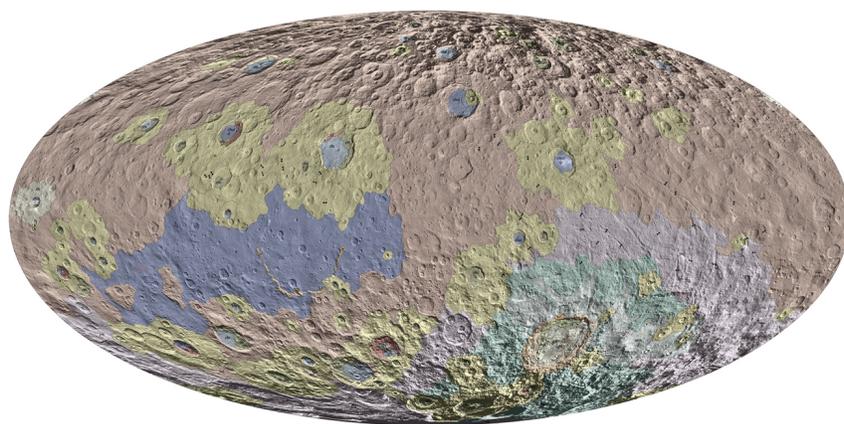
The pre-Kerwanan and Kerwanan Systems are named after the impact event that formed the Kerwan basin. Kerwan is likely among the oldest recognizable impacts preserved within crt, as only a few peaks and arcs of Kerwan’s rim are preserved within the smooth material, making it difficult to date with crater statistics. As crt provides a record of the events that affected the oldest crust now preserved on the surface of Ceres, we use crt to define the boundary between the pre-Kerwanan and Kerwanan. The upper limit for the timing of Kerwan’s formation can be constrained by the smooth material that superposes the basin.

The end of the Kerwanan is marked by the formation of the Yalode impact basin, which is used as the referent for the Yalodean System. During the Yalodean, the Urvara impact basin also formed.

The end of the Yalodean is defined by the formation, or preservation, of “rayed” craters. The largest of these craters include Haulani, Occator, Dantu, and Azacca. Azacca appears to be the oldest of these craters, and is therefore used to define the base of the Azaccan.

Additional analyses of CSFD statistics using both the lunar- and asteroid-derived models will help constrain the boundary AMAs, and ongoing discussions among the team will finalize the chronostratigraphy.

**References:** [1] Russell C.T. et al. (2016) *Science*, **353**, 1008-1010. [2] Williams D.A. et al. (2014) *Icarus*, **244**, 1-12. [3] Yingst R.A. et al. (2014) *PSS*, **103**, 2-23. [4] Buczkowski D.L. et al. (2016) *Science*, **353**, aaf4332. [5] Mest S.C. et al. (2016) GSA Abs. with Programs, #110-7. [6] Williams D.A. et al. (2017) *Icarus*, in review. [7] Roatsch T. et al. (2016) *PSS*, **129**, 103-107. [8] Preusker F. et al. (2016) LPSC, 47, Abstract 1954. [9] Nathues A. et al. (2016) *Nature*, **528**, 237-240. [10] Jaumann R. et al. (2016) LPSC, 47, Abstract 1455. [11] Nathues et al. (2016) *PSS*, **134**, 122-127. [12] Hiesinger H. et al. (2016) *Science*, **353**, aaf4759.



Point Features	Linear Features	Geologic Units	Geologic Units
○ bright spot	— raised rim of large impact crater	<b>s</b> smooth material	<b>ccp</b> crater central peak material
● small tholi	— basin ring	<b>crt</b> cratered terrain	<b>ct</b> crater terrace material
◇ central peak	— degraded impact crater rim	<b>cfs</b> crater floor material smooth	<b>cr</b> crater rim material
◆ knob	— fracture	<b>cfbsb</b> crater floor material smooth bright	<b>ufs</b> Urvara floor material smooth
+ small shield or dome	— impact crater chain	<b>cfbd</b> crater floor material smooth dark	<b>ufr</b> Urvara floor material rugged
	— pit chain	<b>ch</b> crater floor material hummocky	<b>ucp</b> Urvara central peak material
	— ridge crest (1st), accurate	<b>chb</b> crater floor material hummocky bright	<b>ut</b> Urvara terrace material
	— ridge crest (2nd), accurate	<b>chbd</b> crater floor material hummocky dark	<b>ur</b> Urvara rim material
	— scarp	<b>c</b> crater material	<b>uejsl</b> Urvara ejecta material smooth
	— trough	<b>cb</b> crater material bright	<b>uejrl</b> Urvara ejecta material rugged
			<b>yej</b> Yalode ejecta material

Figure 1: Global geologic map of Ceres. Map base is Dawn FC HAMO mosaic (courtesy DLR). Projection is Mollweide; center longitude is 180°E.

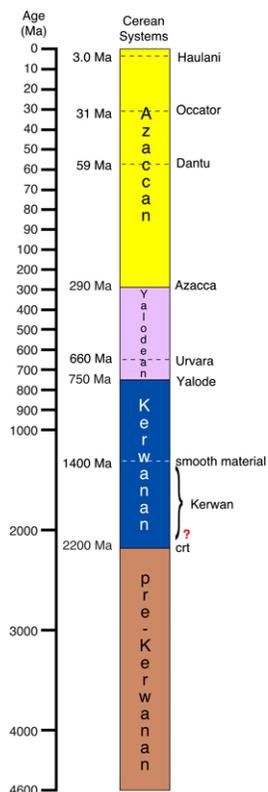


Figure 2. Proposed Cerean chronostratigraphic time system.