

THE GLOBAL LAMO-BASED GEOLOGIC MAP OF CERES

Abstract #7035

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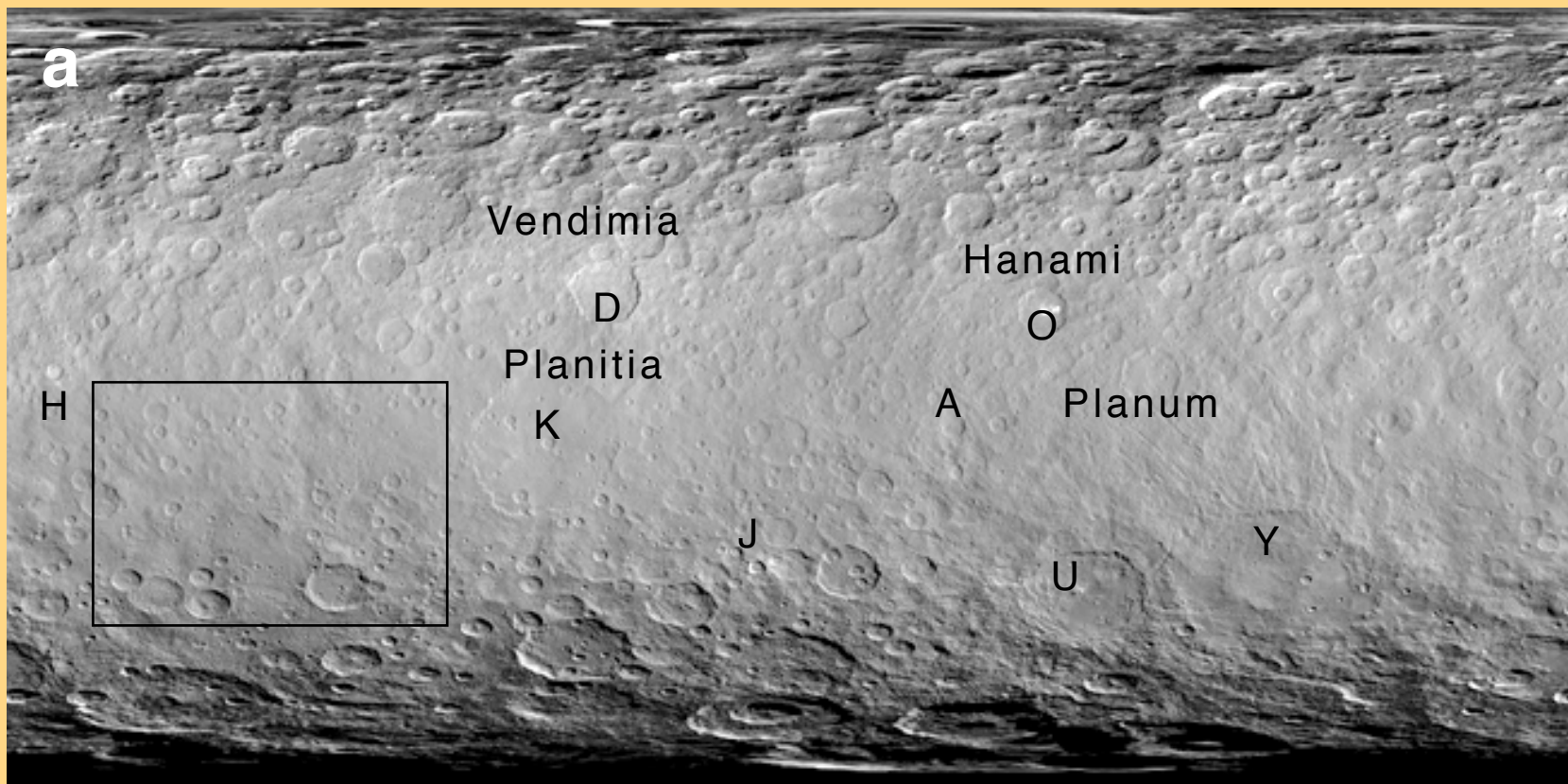
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INTRODUCTION

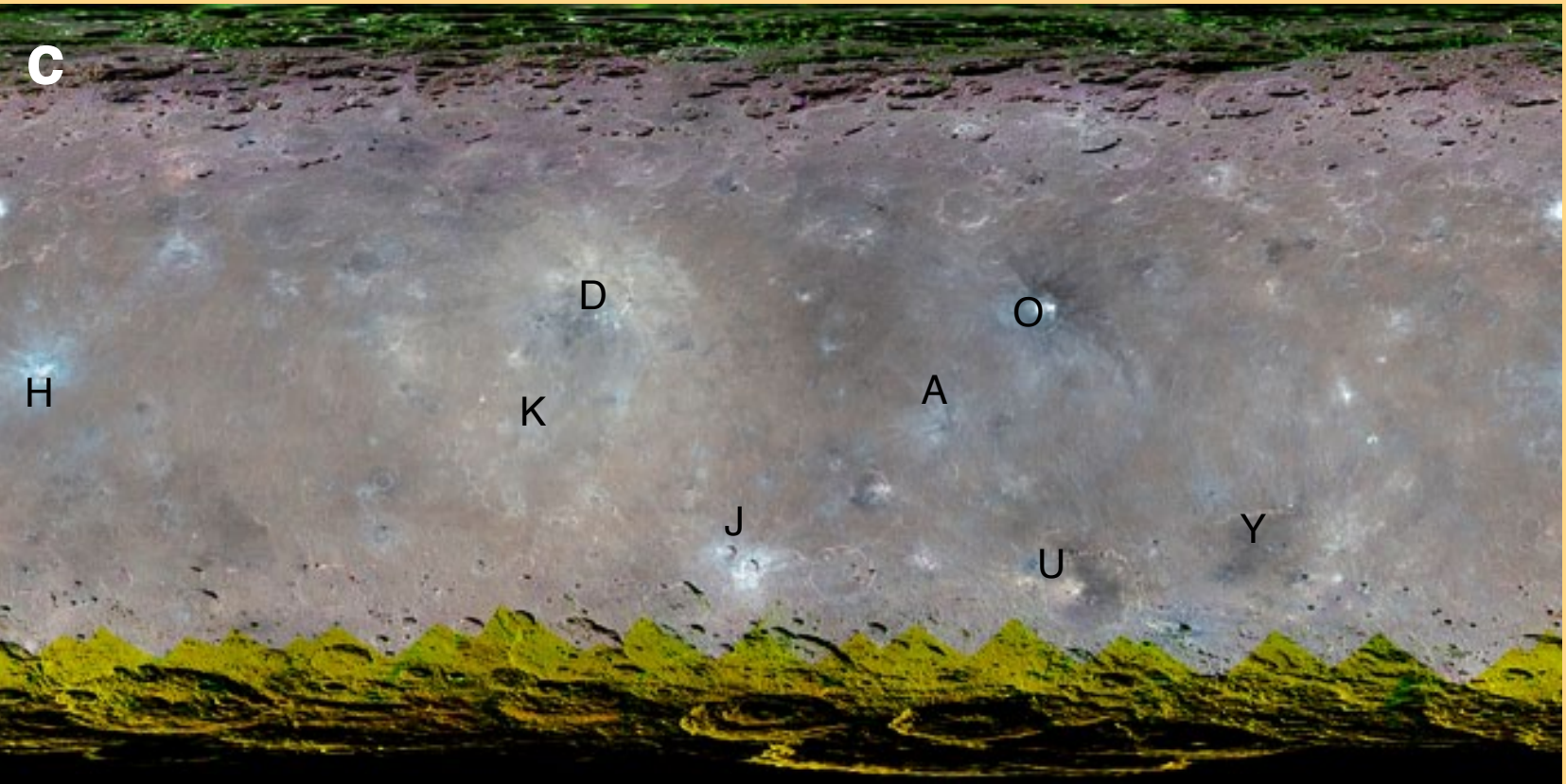
The Dawn mission to Ceres began in 2014 after its successful mission to Vesta. Dawn acquired image, spectral, and topographic data from its approach to Ceres (late 2014) through two extended missions, until its conclusion in October 2018. Images acquired by Dawn during the LAMO phase of the mission provided global coverage at ~35 m/pixel, and images acquired during the extended phases of the mission for several targeted locations, such as Occator crater, have resolutions as high as 2.8 m/pixel.

We are utilizing LAMO-scale Dawn Framing Camera (FC), Visible and Infrared (VIR) Mapping Spectrometer, Gamma Ray and Neutron Detector (GRaND), and derived topographic data (Figure 1) to construct a global geologic map of Ceres based on systematic analysis of the full suite of Dawn mission datasets. This geologic map of Ceres will be published as a U.S. Geological Survey (USGS) Special Investigation Map (SIM) at 1:3M scale for the equatorial region (+/- 60° latitude) and 1:1.5M scale for the polar regions (>60° N and S latitude). Our mapping effort will:

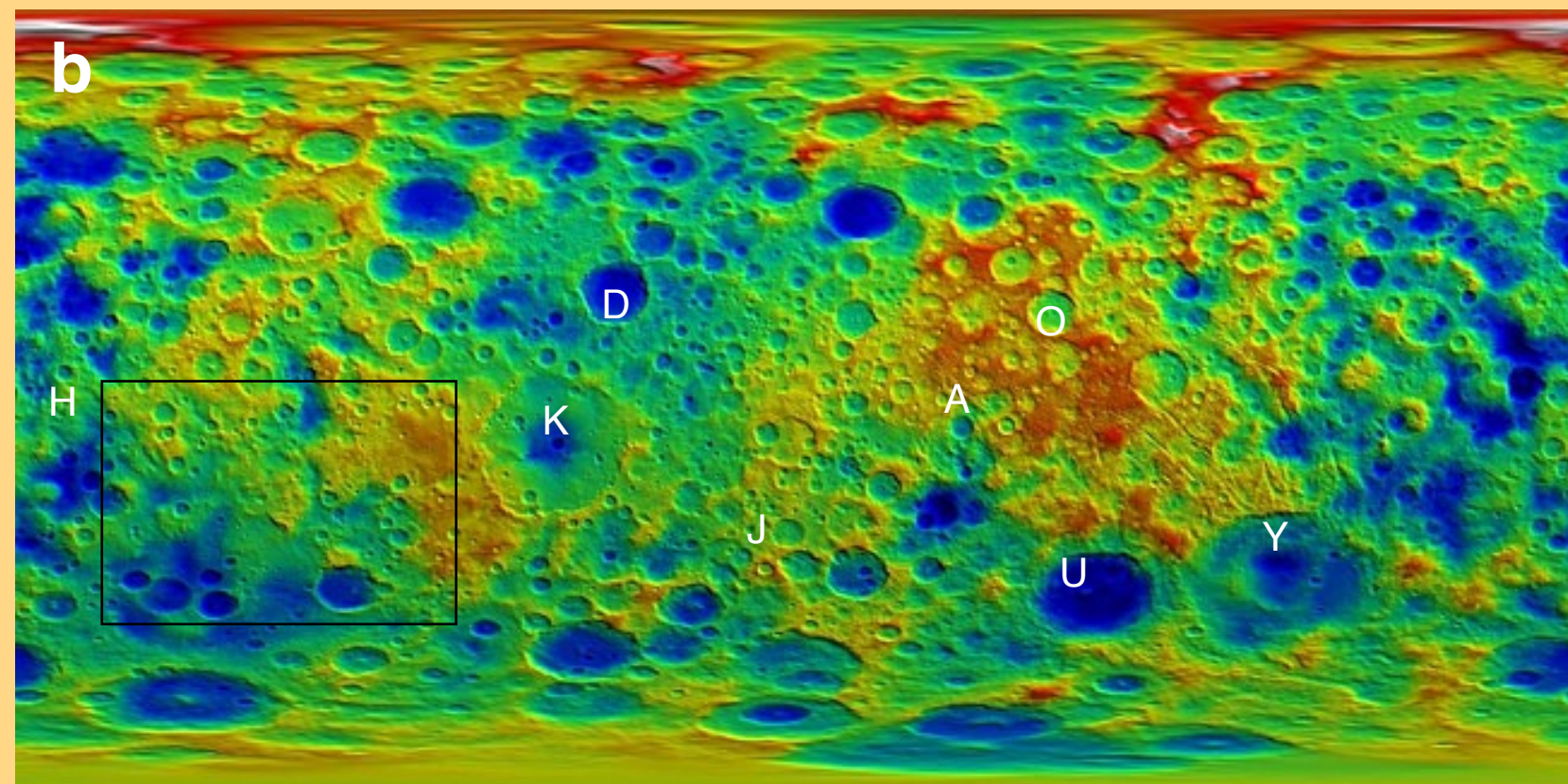
- constrain the lateral extent of the major geologic units observed on Ceres,
- characterize the nature and composition of geologic units, and
- evaluate the temporal relationships of geologic units and events and determine their position within the current Cerean chronostratigraphy



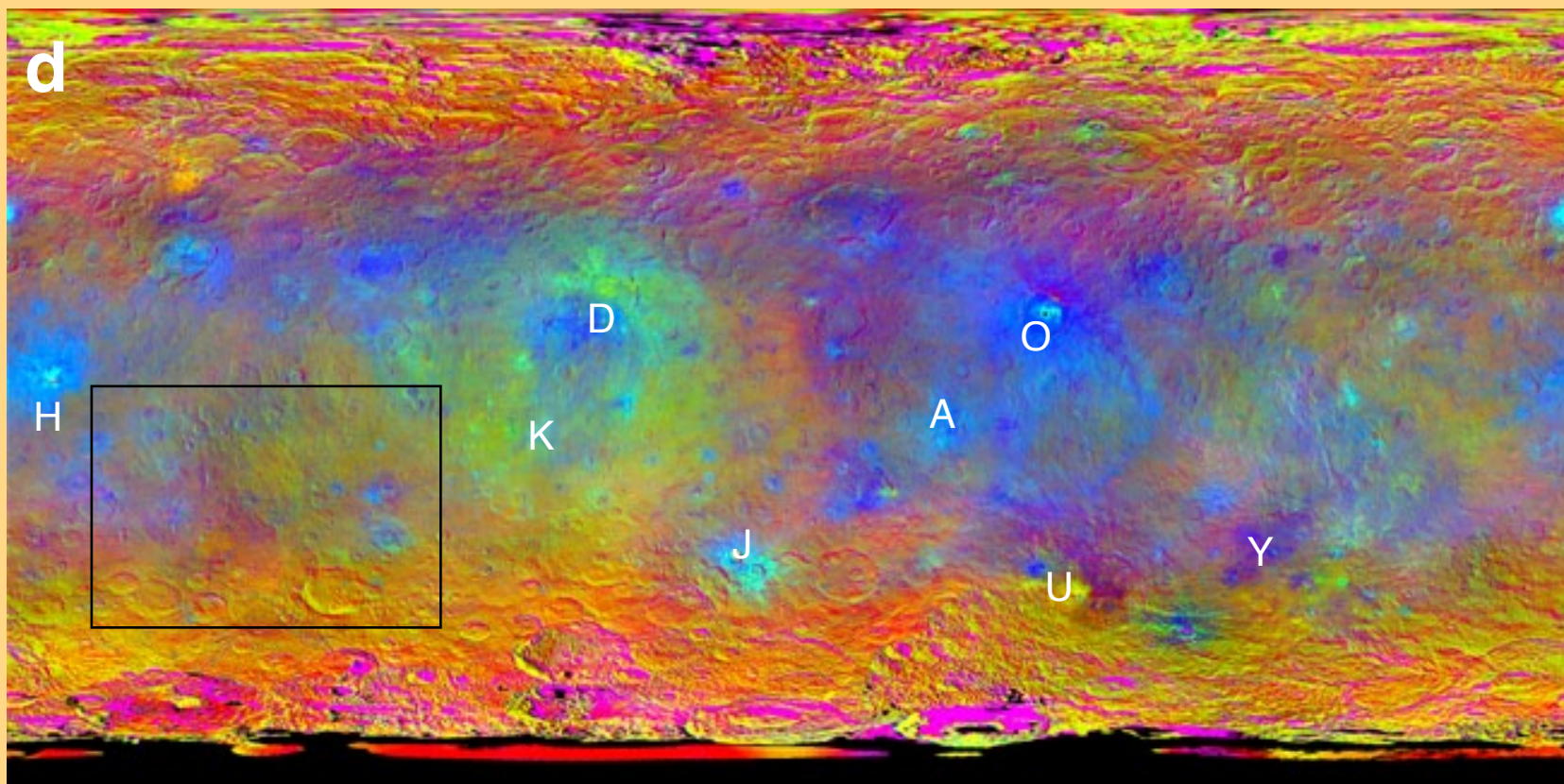
Dawn Framing Camera LAMO mosaic



Dawn Framing Camera HAMO-derived color reflectance



Dawn Framing Camera HAMO-derived DTM



Dawn Framing Camera HAMO-derived color ratio

Figure 1. Dawn datasets to be used in this map effort include (a) FC LAMO mosaic as our primary basemap, and supplemental datasets (b) HAMO-derived DTM, (c) FC HAMO-derived color reflectance map, and (d) HAMO-derived color ratio map where Red=965/750 nm, Green=550/750 nm, and Blue=440/750 nm [9]. Dawn color data will be used to help define the extent of units, such as widespread cratered terrain and smooth material, as well as characterize properties of geologic units. Craters labeled here include H=Haulani, D=Dantu, K=Kerwan, O=Occator, A=Azacca, J=Juling, U=Urvara, and Y=Yalode. Black box shows the location of Figure 3. Global data sets shown here are in equatorial projection covering +/-90° latitude, 0°-360° E longitude.

BACKGROUND

Throughout the Dawn mission to Ceres, iterative geologic mapping was conducted during the Survey, HAMO, and LAMO phases.

Global Survey-based geologic map (Fig. 2a):

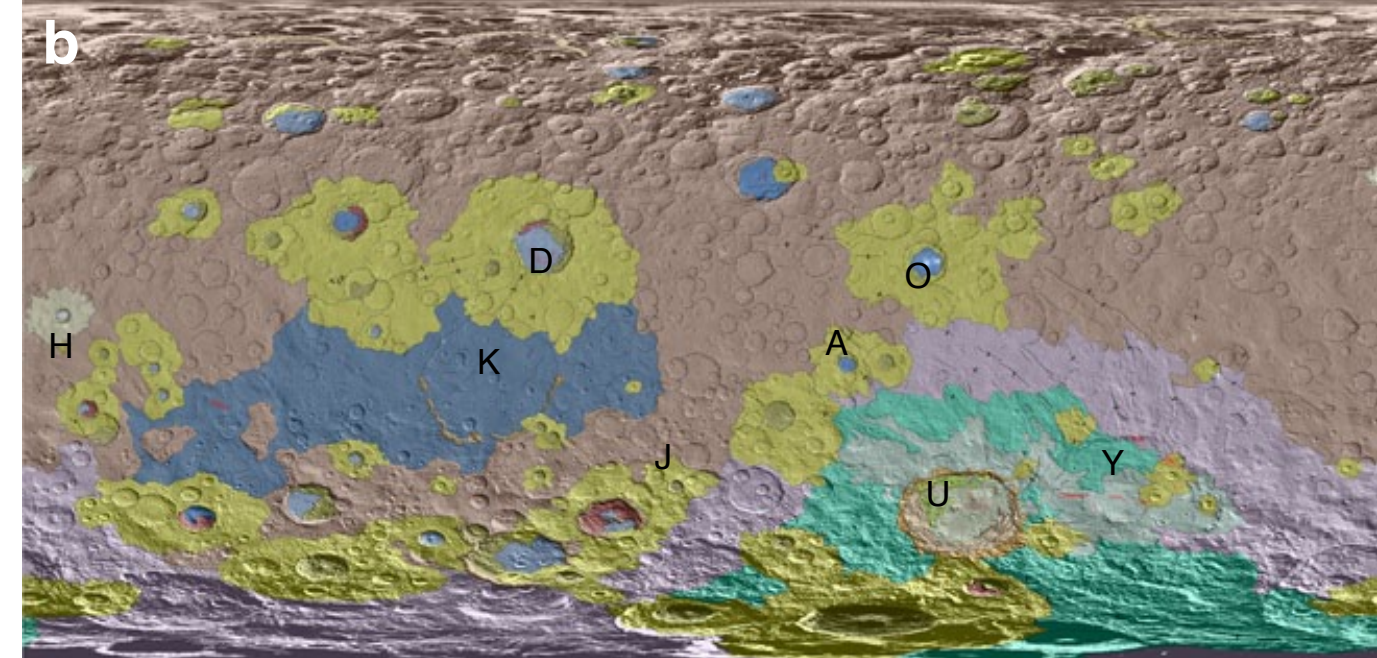
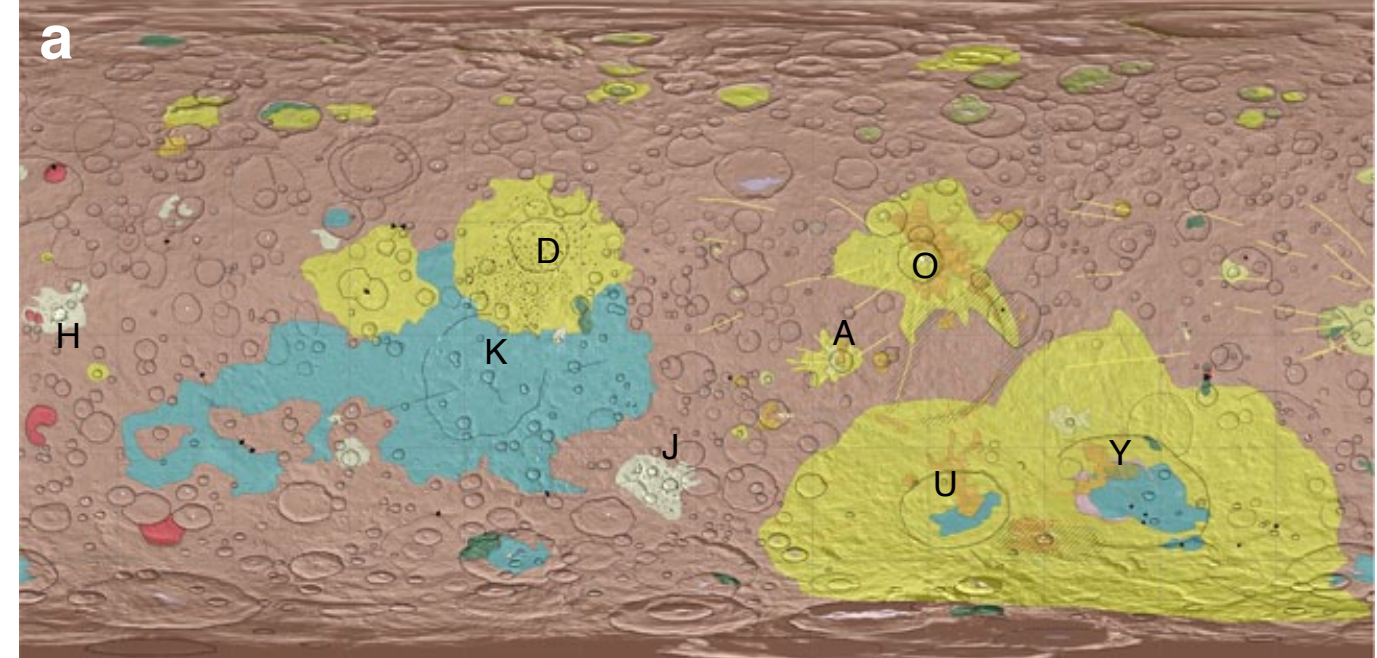
- large number of structures
- 12 geologic units (e.g., cratered terrain, smooth material, undivided crater material)
- albedo differences permitted unique crater materials, e.g. Haulani, to be identified [1-3]

Global HAMO-based geologic map (Fig. 2b):

- more distinct suite of structures
- 21 geologic units [4,5]; constitute three major unit types – upland, plains, and impact materials
- resolutions allowed improvements in observations, surface characterizations, and unit delineation

Quad-scale LAMO-based geologic maps (Fig. 2c):

- global geologic map compiled from 15 quads [see 6 and others within Icarus special issue, 7,8]
- high resolutions allowed significant improvement of feature and geologic unit (45 units) identification and characterization
- however, individual quad maps (a) provide local views of surface, (b) were produced rapidly in short span of time during active mission, and (c) produced by multiple authors with differing mapping styles and objectives; resulted in inconsistencies in levels of detail and interpretations between maps.



HAMO-based Geologic Units	
dpf smooth material	Avccp crater central peak material
dytcr cratered terrain	Avr crater rim material
Avds crater floor material, smooth	Avufs Urvara floor material, smooth
Avdsb crater floor material, smooth bright	Avufb Urvara floor material, rugged
Avdsd crater floor material, smooth dark	Yacp Urvara central peak material
Avdsr crater floor material, hummocky	Yd Urvara terrace material
Avdsrb crater floor material, hummocky bright	Ydr Urvara rim material
Avdsrd crater floor material, hummocky dark	Avues Urvara ejecta material, smooth
Avyc crater material	Avufb Urvara ejecta material, rugged
Acdb crater material, bright	Yys Yalode ejecta material

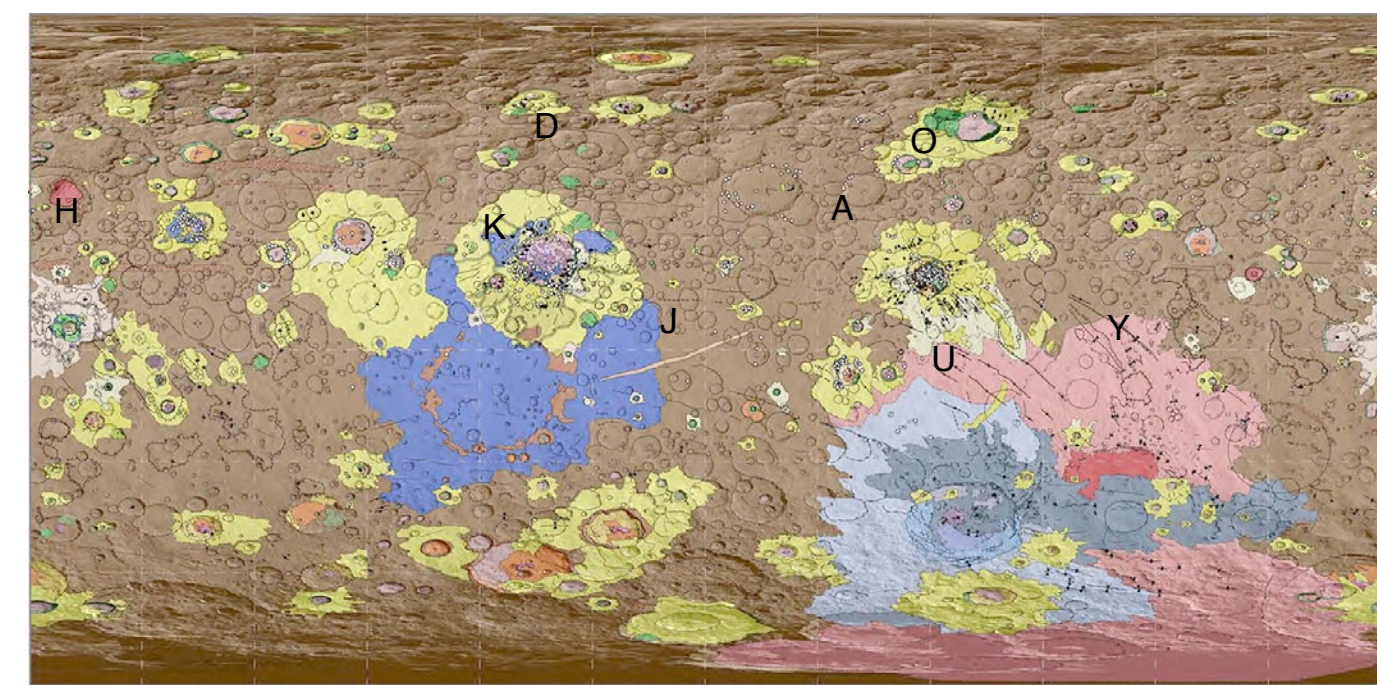


Figure 2. Three iterations of the global geologic map of Ceres from (a) Survey and Approach, (b) HAMO (with legend of units), and (c) LAMO (quad based). Craters labeled here include H=Haulani, D=Dantu, K=Kerwan, O=Occator, A=Azacca, J=Juling, U=Urvara, and Y=Yalode.

MAPPING GOALS

Based on prior HAMO- and LAMO-based mapping studies, our LAMO-based geologic mapping effort has several goals.

First, mapping the cratered terrain will enable us to investigate the unit for any previously unrecognized sub-units, and evaluate the precise areal extent of this unit.

Second, mapping the smooth material will allow for further investigations of the nature of its relationships with other features (such as Kerwan), and the possible origin(s) of this deposit.

Third, mapping impact craters (and other surfaces) at LAMO scale will enable more subtle differences in surface properties (e.g., texture, brightness) to be discerned, which will allow us to accurately define extents of crater materials, characterize types of crater materials, evaluate crater morphologies, and estimate ages of these important stratigraphic markers.

Fourth, incorporation of spectral and mineralogical data into mapping all surfaces will enable compositional signatures to be identified and possible sub-units to be mapped.

Lastly, accurately defining the extents of geologic units is critical in accurately estimating their ages and placing geologic units and events within the Cerean chronostratigraphy [4,5], and documenting Ceres' geologic history.

REFERENCES: [1] Buczkowski, D.L., et al. (2015) DPS, Abstract 212.04. [2] Buczkowski, D.L., et al. (2016) Science, 353. [3] Scully, J.E.C., et al. (2015) DPS, Abstract 212.03. [4] Mest, S.C., et al. (2018) LPS XLIX, Abstract #2730. [5] Mest, S.C., et al. (2021) Icarus, in review. [6] Williams, D.A., et al. (2018) Icarus, 316, 99-113. [7] Nass, A., and the Dawn Science Team (2019) Planetary Geologic Mappers Meeting (LPI Contrib. No. 2154), Abstract #7035. [8] Nass, A., and the Dawn Science Team (2019) EPSC-DPS Joint Meeting, 13, Abstract #1304-2. [9] Nathues, A., et al. (2015) Nature, 528, 237-240. [10] Hiesinger, H., et al. (2016) Science, 353. [11] Otto, K.A., et al. (2016) LPS XLVII, Abstract #1493. [12] Crown, D.A., et al. (2018) Icarus, 316. [13] Neesemann, A., et al. (2019) Icarus, 320, 60-8. [14] Michael, G.G., et al. (2016) Icarus, 277, 279-285. [15] Marchi, S., et al. (2016) Nature Communications, 7. [16] Marchi, S., et al. (2009) The Astron. J., 137, 4936-4948. [17] Marchi, S., et al. (2014) Planet. and Space Sci., 103, 96-103. [18] O'Brien, D.P., et al. (2014) Planet. and Space Sci., 103, 131-142. [19] Pasckert, J.H., et al. (2018) Icarus, 316, 28-45. [20] Scully, J.E.C., et al. (2018) Icarus, 316, 42-62. [21] Crown, D.A., et al. (2018) Icarus, 316, 167-190.

CHRONOSTRATIGRAPHY OF CERES

The HAMO-based global geologic map of Ceres reveals the stratigraphic sequence of map units, which can be placed into a time-stratigraphic scheme to document the global geologic history of Ceres. Establishing a formal chronostratigraphic classification scheme (Figure 4) is important for correlation of distinct and widely separated geologic units on Ceres, as well as to provide a means to correlate Cerean geologic units and events to the geologic histories of other planetary bodies.

Development of the Cerean chronostratigraphy relied upon measuring impact crater diameters globally and determining absolute model ages (AMAs) of Ceres' major geologic units, identified through HAMO-based geologic mapping, and calculation of CSFD statistics for each unit. CSFDs were determined for several geologic units of interest using procedures established for Ceres [13]. The rigorous task of identifying and measuring all craters greater than 100 m in diameter was conducted using Dawn FC images and FC-based DTMs. Here we use the Poisson Timing Analysis (PTA) [14] to evaluate CSFDs. In order to use the measured CSFDs for deriving AMAs, two different chronology models, the Lunar Derived chronology Model (LDM) [10] and the Asteroid-flux Derived chronology Model (ADM) [15-18] were applied.

CEREAN SYSTEMS

The time-stratigraphic scheme for Ceres relates the geologic (rock-stratigraphic) units, identified in (Figure 2b), that are contained within a series of time-stratigraphic (chronostratigraphic) units, and correspond to time (chronologic) units that define a geologic time scale (Figure 4).

pre-Yalodean System: The two oldest Cerean chronostratigraphic systems are divided by the deposits resulting from the Yalode impact event. The pre-Yalodean Period includes all geologic events and deposits emplaced within the time span from the formation of Ceres up to the Yalode impact event, from 4.6 Ga to >1.029 Ga (LDM) or 4.6 Ga to >403 Ma (ADM). Similar to the geologic histories of other rocky bodies (e.g., Moon, Vesta, Mercury, Mars), the pre-Yalodean was dominated by the formation of large impact structures, such as Kerwan (284 km) and Yalode (260 km), large quasi-circular depressions (e.g., Vendimia Planitia) [15], and heavily cratered terrains.

Yalodean System: The base of the Yalodean system is defined by the Yalode impact event and its related deposits, with an age of 1.029 Ga (LDM) or 403 Ma (ADM). The Yalodean Period covers the time span between the Yalode and Azacca impact events, from 1.029 Ga to 223 Ma (LDM) or 403 Ma to 23 Ma (ADM) and represents a time of decreased geologic activity (i.e., reduced cratering rate) on Ceres. A few notable impact craters formed during the Yalodean, including Ezinu, Omonga, Achita, Liber, Ninsar, and Gaue [19,20]. The formation of Urvara crater (170 km) and emplacement of its impact-related units occurs near the end of the Yalodean Period [21].

Azaccan System: The impact event that formed crater Azacca and its associated deposits defines the base of the youngest chronologic system on Ceres, the Azaccan system. The Azaccan Period covers the time span from the Azacca impact event to the present, beginning 223 Ma (LDM) / 23 Ma (ADM). However, it is likely that Azacca materials are highly contaminated by secondary craters from other impacts (e.g., Occator) and is younger than 223 Ma / 23 Ma.

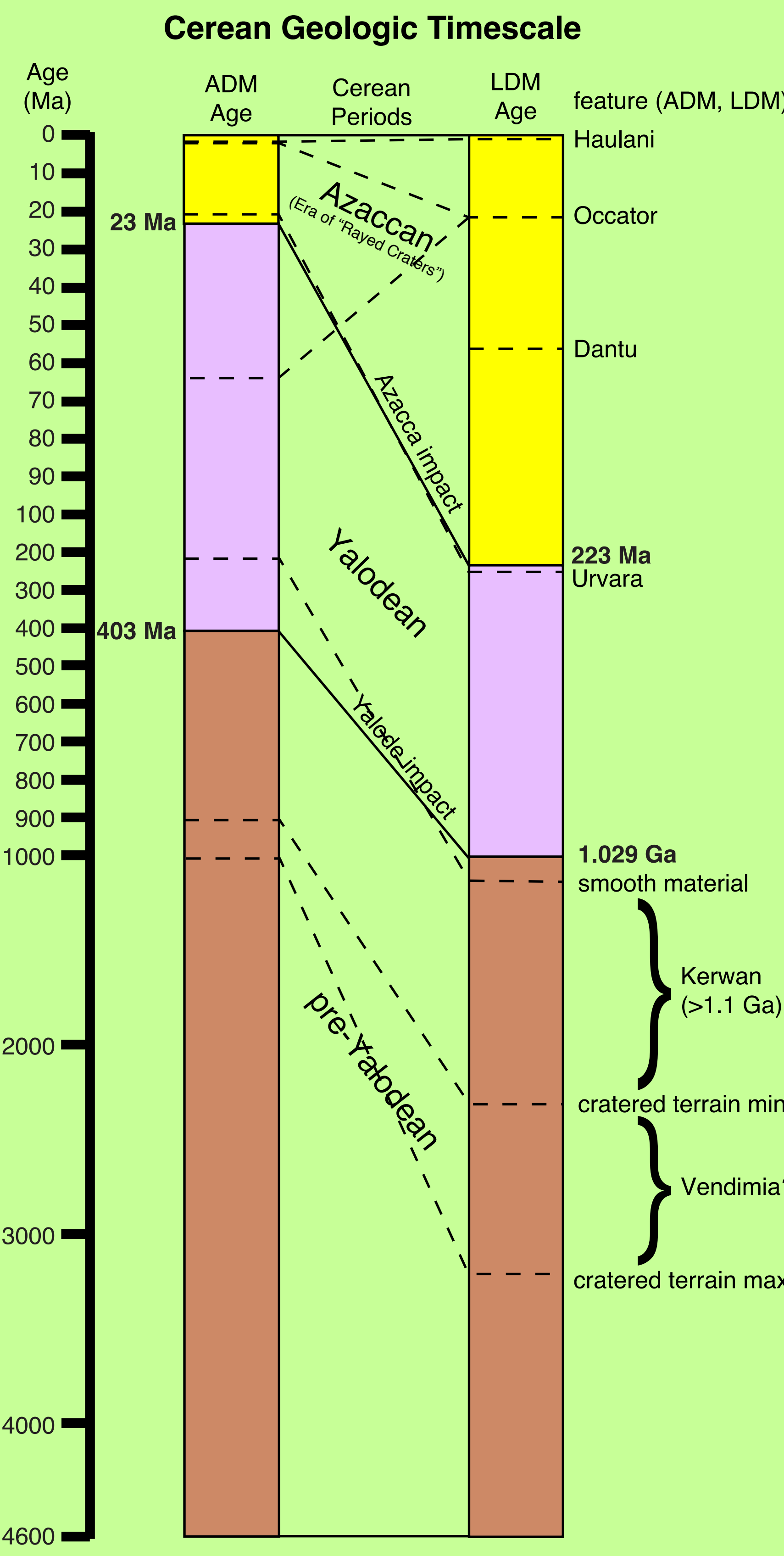


Figure 4. Proposed geologic time scale for Ceres, including the Cerean time units and AMAs of key geologic units and events. The ages are absolute model ages derived from both the lunar-derived (LDM) [10] and asteroid flux-derived (ADM) [11,14-16] chronology systems; note the different age scales for the respective chronology systems.

HAMO-BASED MAPPING RESULTS

Cratered terrain: forms the most widespread continuous unit on the surface of Ceres (Fig. 2) [4,5]; largely undifferentiated except for impact-related units at HAMO scale; consists of rugged and heavily cratered materials with moderate albedo; exhibits topography derived largely from impact structures and includes the oldest surfaces exposed on Ceres; lithology likely consists of crustal materials that have been heavily mixed by impact processes.

Smooth material: forms widespread flat-lying to hummocky plains of moderate albedo in the western equatorial hemisphere (Fig. 2) [4,5]; embays the cratered terrain and is found on the floor of, and surrounding, crater Kerwan; appears featureless at HAMO scale, except for superposing impact structures; underlying hummocky texture, narrow parallel ridges and grooves (western part of the deposit), and buried impact structures observed at higher resolution LAMO images. No clear evidence for its source or emplacement process, but distribution of this unit across high and low elevations suggests it is impact related [4,5].

Impact craters are the most prevalent geologic features on the surface of Ceres, and appear to have caused most of the visible modification of the surface (Fig. 1) [1-6,10]. Impact craters on Ceres exhibit sizes ranging from the limits of resolution to larger structures such as Urvara (170 km), Yalode (260 km), and Kerwan (284 km). Ceres' impact craters exhibit a range of morphologies and preservation styles ranging from morphologically "fresh" to moderately degraded; most craters display rims that are raised above the surrounding terrain and continuous ejecta blankets. Most "fresh" to moderately degraded craters exhibit circular to nearly circular planform shapes, but some have rims that display polygonal planform shapes, reflecting either preexisting fractures in the subsurface and (or) modification of the rim by mass wasting [11].

Impact-related materials: materials generated by impact processes cover large areas of Ceres' surface; form 19 distinct units in the HAMO-scale map (Fig. 2) [4,5]. For larger and morphologically fresh-appearing craters, their deposits are able to be subdivided into distinct geologic facies that are common or recurring across the surface of Ceres. These craters generally show combinations of rim, central peak, floor, and ejecta deposits. In some cases, e.g., Urvara and Yalode, the impact-related deposits are mapped as formations unique to those craters [4,5,12]. Impact craters represent distinct chronological markers in the stratigraphic record of Ceres. Geologic mapping at HAMO scale has identified deposits associated with craters clearly identifiable at HAMO resolutions.

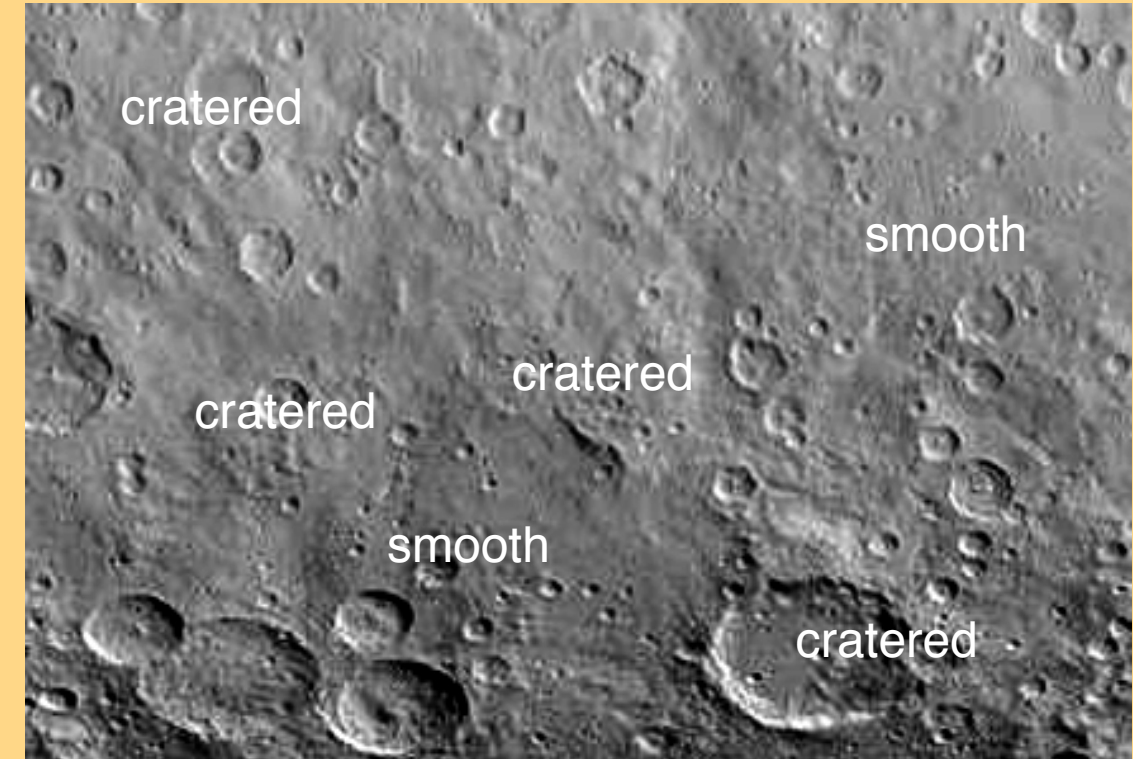


Figure 3. Example of how discrepancies between the distribution of materials have direct effect on interpreting their nature and age. Here, three data sets show different interpretations for this part of the surface. LAMO shows "smooth" material extends throughout the area and is distinct from "cratered" terrain; the DTM shows elevation differences from the upper right to lower left suggesting different materials could be present (arrows point to kipukas of cratered terrain mapped in the HAMO map); the color ratio map shows a large "yellow-green" unit (dashed line) where smooth material is present, but is diffuse elsewhere.