

## THE EVOLUTION OF OCCATOR CRATER AND ITS FACULAE REVEALED BY HIGHEST RESOLUTION OBSERVATIONS OF CERES. J.E.C. Scully<sup>1</sup>, P.M. Schenk<sup>2</sup>, D.A. Williams<sup>3</sup>, D.L. Buczkowski<sup>4</sup>, J.H. Pasckert<sup>5</sup>, K.D. Duarte<sup>6</sup>, V.N. Romero<sup>6</sup>, M.M. Sori<sup>7</sup>, M. Landis<sup>8</sup>, L.C. Quick<sup>9</sup>, B.E. Schmidt<sup>6</sup>, C.A. Raymond<sup>1</sup>, J.C. Castillo-Rogez<sup>1</sup>, C.T. Russell<sup>10</sup>, <sup>1</sup>Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA, <sup>2</sup>LPI, Houston, TX, USA, <sup>3</sup>ASU, Tempe, AZ, USA, <sup>4</sup>JHU-APL, Laurel, MD, USA, <sup>5</sup>Institute für Planetologie, WWU Münster, Germany, <sup>6</sup>Georgia Institute of Technology, Atlanta, GA, USA, <sup>7</sup>LPI, Tucson, AZ, USA, <sup>8</sup>PSI, Tucson, AZ, USA, <sup>9</sup>National Air & Space Museum, Smithsonian Institution, Washington DC, USA, <sup>10</sup>UCLA, Los Angeles, CA, USA.

**Introduction:** The Dawn mission explored Ceres, the largest object in the asteroid belt, from 2015-2018 [1]. Occator crater (92 km diameter) contains enigmatic interior bright regions, named Cerealia Facula and Vinalia Faculae. The faculae are six times brighter than Ceres' average [2], are mostly sodium carbonate [3] and are only a few millions of years old [4].

**Previous Work:** A special issue of *Icarus* sought to uncover the driving forces behind the formation of Occator and its faculae [5], using data acquired from ~385 km in altitude during Dawn's prime and first extended missions. The special issue synthesis concluded that the features formed during stage 1 of Occator's evolution (e.g. lobate material, central pit) could be explained by impact-derived driving forces only, while the subsequent formation of the faculae and related features (stage 2) may require an endogenic component [6]. During stage 3, there was later localized modification of the faculae and the crater floor.

**Results from Dawn's Second Extended Mission (XM2):** During XM2, low elliptical orbits from <50 km perihelion altitude provided Framing Camera (FC) images of Occator with a ground sampling distance as low as ~5 m/pixel. Here we revisit the *Icarus* special issue conclusions, in light of the order of magnitude spatial resolution improvement provided by the XM2 data.

**XM2-Based Geologic Mapping.** Geologic mapping provides a methodically-derived and self-consistent interpretation of the data that cannot be achieved by visual inspection alone. We updated the geologic map of Occator's interior using XM2 FC images. We mapped the entire crater interior at 1:50,000 and the faculae at 1:10,000. We used a combination of 2D mapping in ArcMap and 3D mapping in ArcScene, which facilitated greater insights into the placement of contacts, stratigraphic relationship etc. than 2D mapping alone. Our basemap is the XM2 clear filter FC mosaic by DLR [7].

**XM2-Based Updates to Geologic History.** Our XM2 geologic map is a tool to understand the spatial distribution of, and stratigraphic relationships between, features in Occator, resulting in a geologic history that is broadly consistent with the *Icarus* special issue [6]. However, there are new, important updates, discussed below.

**Stage 1.** The lobate material is a slurry, formed when impact-melted water ice with entrained blocks of unmelted silicates and salts flowed around the crater

interior before solidifying [6,9]. It is apparent from the XM2 data that the lobate material coats almost the entire crater interior. While the large, thick sheet (label a in figure) and smaller, isolated, pond-like deposits of lobate material were observed in pre-XM2 data, the thinner veneer of lobate material that coats the majority of the terraces and the crater floor is only clearly visible in the XM2 images (label b in figure). The thin veneer sometimes forms a cap on top of terraces, which breaks off at the steeply sloping terrace edges. In the XM2 data there are also multiple instances of lobate material flows spectacularly superposing one another. The lobate material has different surface textures, some of which are consistent with pre-XM2 data (e.g. smooth and hummocky lobate material), and some of which we updated based on the XM2 data (e.g. smooth lobate material interspersed with knobs and striations). Mounds are also evident in the XM2 data. They are mostly located in the lobate material and may have been formed by eruptive processes and/or frost-heave-like processes [8] derived from solidification/expansion of the lobate material.

In the XM2 data, the southern part of the central pit (label c in figure) appears to be a warped part of the thick lobate material sheet. Stratigraphic relationships we observe in the XM2 data indicate that the central pit, its concentric fractures and the outer edge of Cerealia Facula formed during stage 1, which is consistent with the pre-XM2 conclusions [6]. For example, while the majority of Cerealia Facula formed during stage 2, its outer edge tends to be cut by the concentric fractures, indicating it formed prior to the central pit.

**Stage 2.** The majority of Cerealia Facula (label d in figure) is interior to its outer edge, coats the bottom and sides of the central pit and is thought to be emplaced by short-lived brine flows/fountains [e.g. 6, 9-11]. We interpret that the majority of Cerealia Facula was emplaced after the formation of the central pit because the deposit does not display cracks and/or compressional features in the XM2 data, which would be expected if the deposit was emplaced prior to pit formation. The regular correlation between topography and the Cerealia Facula (which is located in the lows of the central pit and in between the massifs adjacent to the central pit) is also consistent with pit formation occurring first.

There are no flow fronts or obvious source regions for the bright faculae deposits in the XM2 data.

However, the numerous localized bright material point features that surround both Cerealia and Vinalia Faculae are more clearly resolved in the XM2 data. These are likely individual bright material sources. The XM2 data also illustrates that faculae material is often perched on ledge-like areas of the high massifs adjacent to the central pit. The most notable is to the west of the central pit (label e in figure) and sources bright material landslides.

The higher resolution XM2 data illustrates that not all dark patches within the Cerealia Facula are topographic highs. There are also instances of dark material mass wasting on top of bright faculae material. Both of these observations indicate that the dark material is not simply a passive bystander that is either coated or not covered by the bright faculae material.

Our XM2-based mapping also reveals that the fractures from which the Vinalia Faculae (label f in figure) were previously proposed to originate [4,6,9-10,12] actually cut through the Vinalia Faculae. If these fractures did source the Vinalia Faculae, later reactivation must have resulted in the current cross-cutting relationship. The fractures often open out into broad pits that are coated by dark material and occasional bright material landslides originating from the Vinalia Faculae.

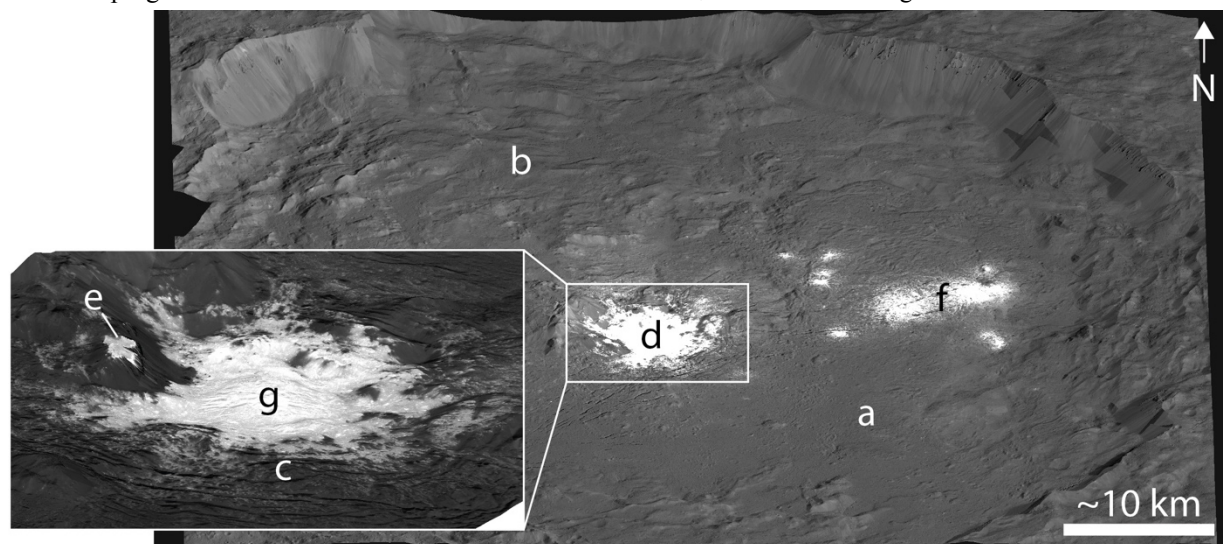
The central dome is located in the base of the central pit (label g in figure), is entirely coated by Cerealia Facula and appears to be one of the last features formed within the crater [4,6,9-12]. In the XM2 data, there is no dark material at the bases of the fractures on the central dome, giving a lower limit to the thickness of the bright material in this area. There is also no termination scarp observed around the base of the central dome in the XM2 data, perhaps indicating that it was formed intrusively. Alternatively, if formed extrusively, the lack of a scarp leads to a constraint on material viscosity, which is work in progress.

**Stage 3.** There are numerous bright and dark point features superposing the faculae in the XM2 data. Some are bright and dark ejecta from impact craters, which lead to localized thickness estimates of the faculae.

**Conclusions:** We derive the following main insights from our XM2-based geologic mapping: (1) the lobate material coats almost the entire crater interior, and the southern part of the central pit appears to be a warped part of the lobate material, (2) the faculae-forming brines seeped onto the surface from multiple, individual sources, rather than all originating from one dominant location, (3) the majority of Cerealia Facula was emplaced after the formation of the central pit, (4) if the Vinalia Faculae were sourced in their cross-cutting fractures, there must have been later reactivation due to a regional stresses, and (5) dark material is sometimes emplaced on top of/after bright faculae material.

We are presently exploring the possibility that the faculae-forming brines were squeezed out of the solidifying lobate material. However, the ~20 Myr time difference [4] between faculae and crater formation may require a longer-lived brine source from below the lobate material, such as an impact-induced melt and/or an endogenic reservoir that pre-dated crater formation [13].

**References:** [1] Russell et al. (2016) *Science*, 353, 1008-1010. [2] Schröder et al. (2017) *Icarus*, 288, 201-225. [3] De Sanctis et al. (2016) *Nature*, 536, 54-57. [4] Nathues et al. (2019) *Icarus*, in press, and references therein. [5] Scully et al. (2019a) *Icarus*, in press. [6] Scully et al. (2019b) *Icarus*, in press, and references therein. [7] Roatsch et al. (2018) *AGU*, P33D-3869. [8] Schmidt et al. (2018) *AGU*, P24A-04. [9] Schenk et al. (2019) *Icarus*, in press. [10] Ruesch et al. (2019) *Icarus*, in press. [11] Quick et al. (2019) *Icarus*, in press. [12] Buczkowski et al. (2019) *Icarus*, in press. [13] Hesse and Castillo-Rogez (2018) *GRL*, doi: 10.1029/2018gl080327.



**Figure.** Perspective views of Occator crater (main) and Cerealia Facula (inset) in XM2 data [7].