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# Synthesis of the special issue: The formation and evolution of Ceres' Occator crater

Jennifer E.C. Scully[a,*], Timothy Bowling[b], Caixia Bu[c], Debra L. Buczkowski[d], Andrea Longobardo[e], Andreas Nathues[f], Adrian Neesemann[g], Ernesto Palomba[e], Lynnae C. Quick[h], Andrea Raponi[e], Ottaviano Ruesch[i], Paul M. Schenk[j], Nathan T. Stein[k], E.C. Thomas[a,l], Christopher T. Russell[m], Julie C. Castillo-Rogez[a], Carol A. Raymond[a], Ralf Jaumann[n], the Dawn Science Team

[a] Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA
[b] Southwest Research Institute, Boulder, CO 80302, USA
[c] University of Virginia, Charlottesville, VA 22903, USA
[d] Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, USA
[e] Institute for Space Astrophysics and Planetology, National Institute for Astrophysics (INAF/IFSI), Rome 00133, Italy
[f] Max Planck Institute for Solar System Research, Göttingen 37007, Germany
[g] Free University of Berlin, Berlin 14195, Germany
[h] Center for Earth and Planetary Studies, National Air and Space Museum, Smithsonian Institution, Washington, DC 20560, USA
[i] NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
[j] Lunar and Planetary Institute, Houston, TX 77058, USA
[k] California Institute of Technology, Pasadena, CA 91125, USA
[l] NASA Astrobiology Institute
[m] University of California, Los Angeles, CA 90095, USA
[n] German Aerospace Center (DLR), Berlin 12489, Germany

## ABSTRACT

The distinctive bright regions within Occator crater are one of the most remarkable discoveries of the Dawn mission's exploration of Ceres. The central region is named Cerealia Facula and the additional regions in the eastern crater floor are named Vinalia Faculae. Here we summarize and synthesize the results of this special issue, which aimed to identify the driving forces behind the formation of Occator and the faculae, and thus lead us to a new understanding of the processes and conditions that occurred in Ceres' past, and potentially in its present. The investigations presented here used Dawn data, theoretical modeling and laboratory experiments to deduce the sequence of events that led to the formation of Occator, Cerealia Facula and Vinalia Faculae, which are broken into stages 1–3. Stage 1: Occator's ejecta blanket, terraces and hummocky crater floor material formed during and shortly after crater formation. These features are located in many Cerean complex craters. However, Occator also contains the lobate materials and faculae, which are unique to Occator. We interpret the lobate materials as a slurry of water, soluble salts and boulders of unmelted silicates/salts, which flowed around the crater interior before solidifying. At least portions of the lobate materials were solidified prior to the formation of the central pit, which is suggested to form via the 'melted uplift model' and provides insights into central pit formation across the Solar System. We propose the outer edge of Cerealia Facula formed shortly after the Occator-forming impact, via impact-induced hydrothermal brine deposition or via salt-rich water fountaining (perhaps sourced in a pre-existing reservoir). Stage 2: the majority of Cerealia Facula is located within the central pit and is interpreted to have formed later, at least ~18 Myr after the Occator-forming impact, via multiple depositional events. The Cerealia-Facula-forming brines may have flowed out of fractures in the walls of the central pit and/or been driven to the surface by freezing of a subsurface reservoir and/or deposited via salt-rich water fountains. Further investigations are required to identify whether the formation of the majority of Cerealia Facula is driven by processes triggered by an impact, i.e. an exogenic event, or by a combination of impact-driven and endogenic processes. Cryomagmatic intrusions are suggested to uplift the crater floor, resulting in concentric floor fractures and an asymmetric dome. Injection of a similar material is proposed to inflate part of the lobate materials, giving them a hummocky texture. The resulting stresses formed fractures in the hummocky lobate material, which allowed the Vinalia-Faculae-forming brines to travel to the surface, where they ballistically erupted. The central dome within the central pit was one of the last features to form, by laccolithic intrusion, or by volume expansion from freezing of volatiles, or by extrusion of brines. Stage 3: mixing with Ceres' average materials and/or space weathering darken the faculae over time. Cerealia Facula and Vinalia Faculae are the brightest and freshest of the bright regions identified on Ceres' surface. Bright regions darken over time until their eventual erasure. Thus, it is likely that faculae formation has occurred throughout Ceres' history, but that Occator's faculae are visible today because they are geologically young. Through synthesis of the studies presented in this special issue, we find that entirely exogenic driving forces, triggered by the impact, or a combination of endogenic and impact-derived forces could explain the formation of Occator and its faculae. Whether activity is impact-triggered and/or endogenic in nature is a key question for all investigations of Ceres, and

* Corresponding author.
*E-mail address:* jennifer.e.scully@jpl.nasa.gov (J.E.C. Scully).

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future studies may favor one possibility over the other. The investigations presented in our special issue indicate Ceres is an active world where brines have been mobile in the geologically recent past. As such, Ceres is an intriguing world that we have only begun to explore.

## 1. Introduction

The aim of this special issue was to identify the driving forces behind the formation of Occator crater and its interior bright regions: Cerealia Facula and Vinalia Faculae (Fig. 1). Occator and its faculae were observed by the Dawn mission, which in 2015 became the first spacecraft to visit Ceres (Russell et al., 2016). Ceres is billions of years old while Occator is tens of millions of years old, on the basis of the

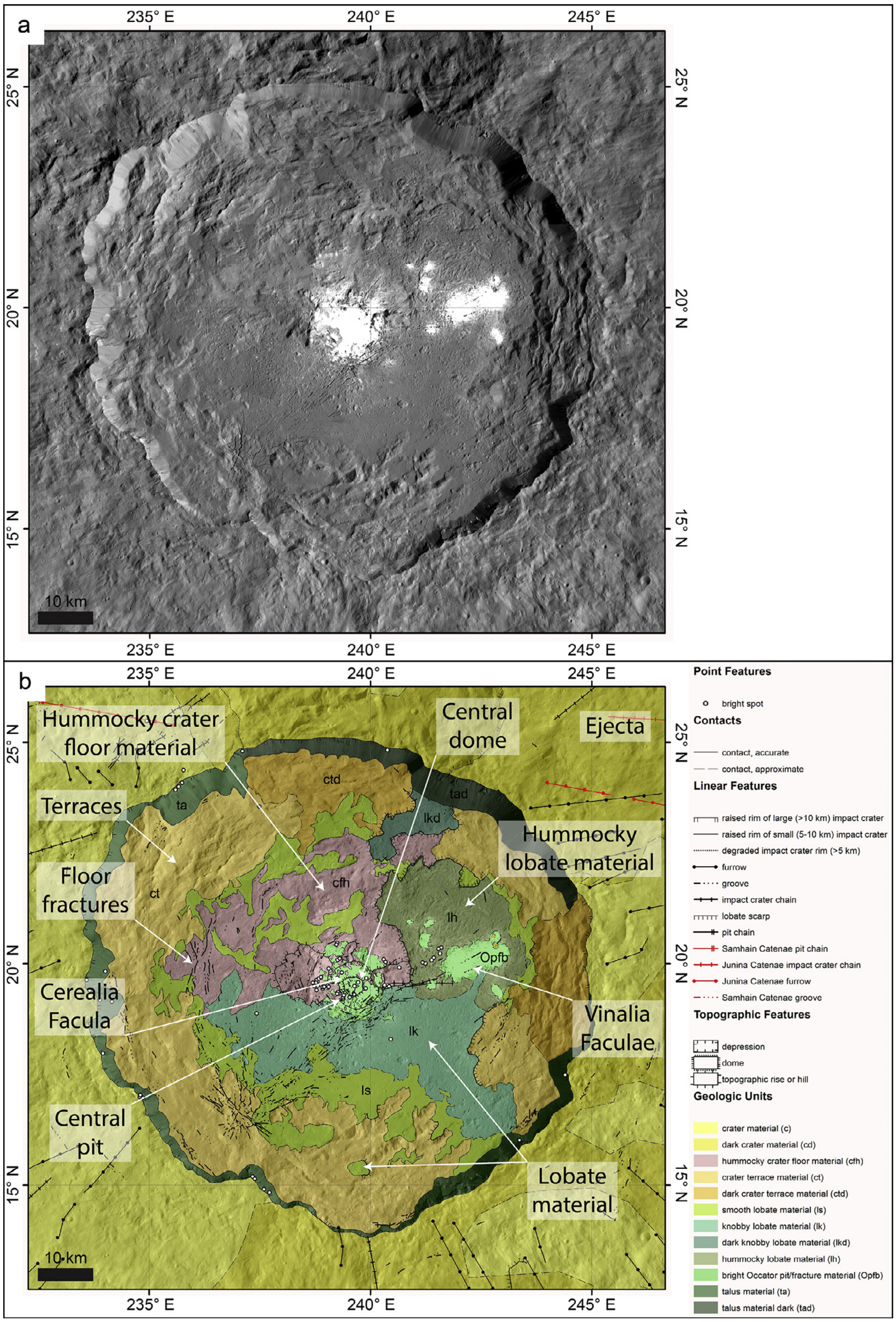


**Fig. 1.** (a) A mosaic of Occator crater, made from clear filter Framing Camera images (~35 m/pixel) by the German Aerospace Center (DLR) (Roatsch et al., 2017). This mosaic is displayed with an equirectangular projection. (b) The geologic map of Occator crater made by Scully et al. (2018b), which is overlain onto the mosaic of Occator crater. Prominent features discussed in the text are labeled and the legend for the geologic map is displayed on the right (discussed in detail in Scully et al. (2018b)). This figure was adapted from Figs. 2 and 4 in Scully et al. (2018b).

lunar derived chronology model (Nathues et al., 2017; Neesemann et al., 2018). Occator's faculae appear to be younger than the crater itself, with ages estimated on the order of a few millions of years, also on the basis of the lunar derived chronology model (Nathues et al., 2017). In this special issue, we investigate whether the driving forces behind the formation of Occator and its faculae are primarily exogenic (i.e. impact derived), primarily endogenic or a combination of both. Our goal is for the resulting insights to lead us to a new understanding of the processes and conditions in Ceres' past, and, because of the relative youth of the faculae, potentially at present. For additional information about the motivation and goals of this special issue, and background about Ceres, the Dawn mission and Occator crater see Scully et al. (2018a). In this paper we first summarize all of the papers in this special issue (see Section 2). We then synthesize the insights from these papers into the sequence of events that formed Occator and its faculae (see Section 3). We close with a discussion of the implications (see Section 4).

## 2. Summary of papers in this special issue

### *2.1. Summary of Scully et al.: Ceres' Occator crater and its faculae explored through geologic mapping*

Scully et al. (2018b) use high-resolution Framing Camera images (~35 m/pixel) to create a detailed geologic map of Occator crater's interior and ejecta (Fig. 1). The asymmetric ejecta blanket indicates that the Occator-forming impactor originated from the northwest at an angle of ~30–45°, perhaps closer to ~30°. The authors map geologic units of crater terrace material, hummocky crater floor material and talus material within Occator, which are also found within other complex craters in the region.

The lobate materials and the bright Occator pit/fracture material (this is the unit that corresponds to the Cerealia Facula and Vinalia Faculae) are the geologic units that make Occator unique. On the basis of geomorphological evidence derived from their geologic map, the authors propose that the lobate materials are a slurry of impact-melted and non-impact-melted target material, which flowed around the crater interior before solidifying to form deposits geomorphologically consistent with impact melts elsewhere in the Solar System. This interpretation is consistent with the impact simulations of Bowling et al. (2018), the morphological analysis of Schenk et al. (2018), and one set of model ages of Occator (Neesemann et al., 2018), but not with the other set of model ages (Nathues et al., 2018). The lobate materials are divided into smooth lobate material, knobby lobate material and hummocky lobate material on the basis of their surface textures, which reflect different emplacement mechanisms and post-emplacement modification.

Scully et al. identify one set of stratigraphic relations within the Cerealia Facula region and another set of stratigraphic relations within the Vinalia Faculae region. However, there are no clearly defined stratigraphic relations identified between Cerealia Facula and Vinalia Faculae. Cross-cutting relationships indicate that the knobby lobate material and much of the outer edge of Cerealia Facula were emplaced prior to the formation of Occator's central pit (Fig. 2). After the formation of the central pit, the central dome formed, and the inner part of Cerealia Facula, which is found to be at least ~30 m thick, may have formed, continued to form and/or have been modified. The surficial Cerealia Facula material has likely darkened somewhat since it was initially emplaced, because small impact craters and their ejecta blankets expose even brighter material from depth.

The Vinalia Faculae are located on, and formed after, the hummocky lobate material and are found to be less than 50–100 m thick (Fig. 1). The diffuse morphology of the Vinalia Faculae is reminiscent of the discontinuous diffuse material that forms the outer edge of Cerealia Facula. This suggests that the Cerealia Facula may have initially been emplaced in similar process to the Vinalia Faculae, consistent with Quick et al. (2018) and Ruesch et al. (2018a). Scully et al. suggest that the current morphological differences between Cerealia Facula and Vinalia Faculae may be due the continued formation/modification of the Cerealia Facula and the formation of the central dome.

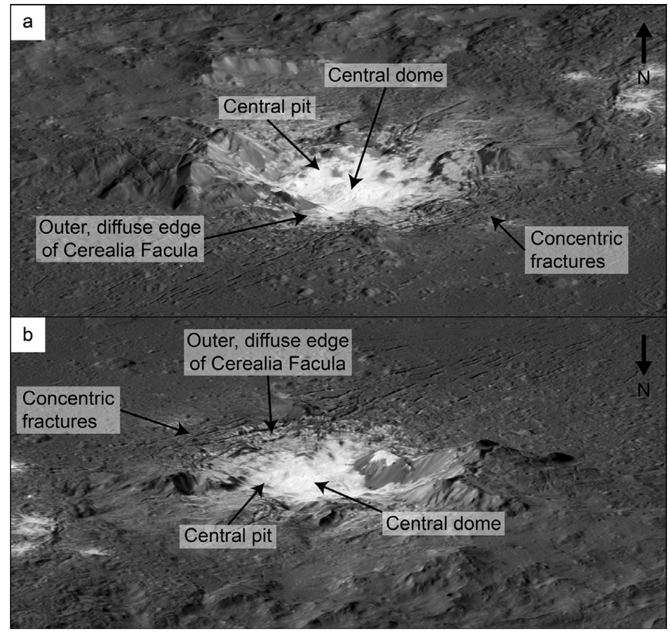


**Fig. 2.** Perspective views of the center of Occator crater. Image (a) is from the south looking north and image (b) is from the north looking south. The perspective views have no vertical exaggeration and were made by David P. O'Brien (Planetary Science Institute) by overlaying Framing Camera clear filter images (~35 m/pixel) onto the shape model of Occator (Jaumann et al., 2017). This figure was adapted from Fig. 8 in Scully et al. (2018b).

### *2.2. Summary of Nathues et al.: Occator crater in color at highest spatial resolution*

Nathues et al. (2018) use high-resolution Framing Camera color data (~35 m/pixel) to investigate the formation and evolution of Occator crater and the faculae. The authors find that the ejecta surrounding Occator is asymmetrically distributed. Ejecta rays extend for up to ~500 km, and are particularly distinct in the color data. The ejecta does not appear as fluidized as ejecta from craters such as Haulani and Kupalo. The ejecta and crater interior in the northeast display different spectral behavior than the other regions. This is highlighted in the enhanced color mosaic (R = 0.96 μm, G = 0.75 μm, and B = 0.44 μm), where the majority of the crater floor appears blue and the northeastern region appears brown.

The non-uniform distribution of the faculae within the crater is interpreted to be due to either an uneven distribution of subsurface brines or significant variations in the thickness of the crater floor. One possible interpretation of the cluster of fractures in the southwestern crater floor is that bright material sourced in a subsurface reservoir was prevented from reaching the surface by an overlying surface layer that is thicker than the layer underlying the faculae.

The association of the Vinalia Faculae with fractures whose sides are coated with bright material leads to the conclusion that the Vinalia Faculae originate from these fractures, consistent with Nathues et al. (2017). The Vinalia Faculae are estimated to be a few meters thick and are entirely confined within the lobate material in Occator's floor. This indicates that they formed after the lobate material, which is interpreted as a debris avalanche deposit. Using a Poisson timing analysis, the lack of resolvable impact craters superposing the Vinalia Faculae leads to the interpretation that the Vinalia Faculae formed < 2 million years ago, long after the formation of Occator itself.

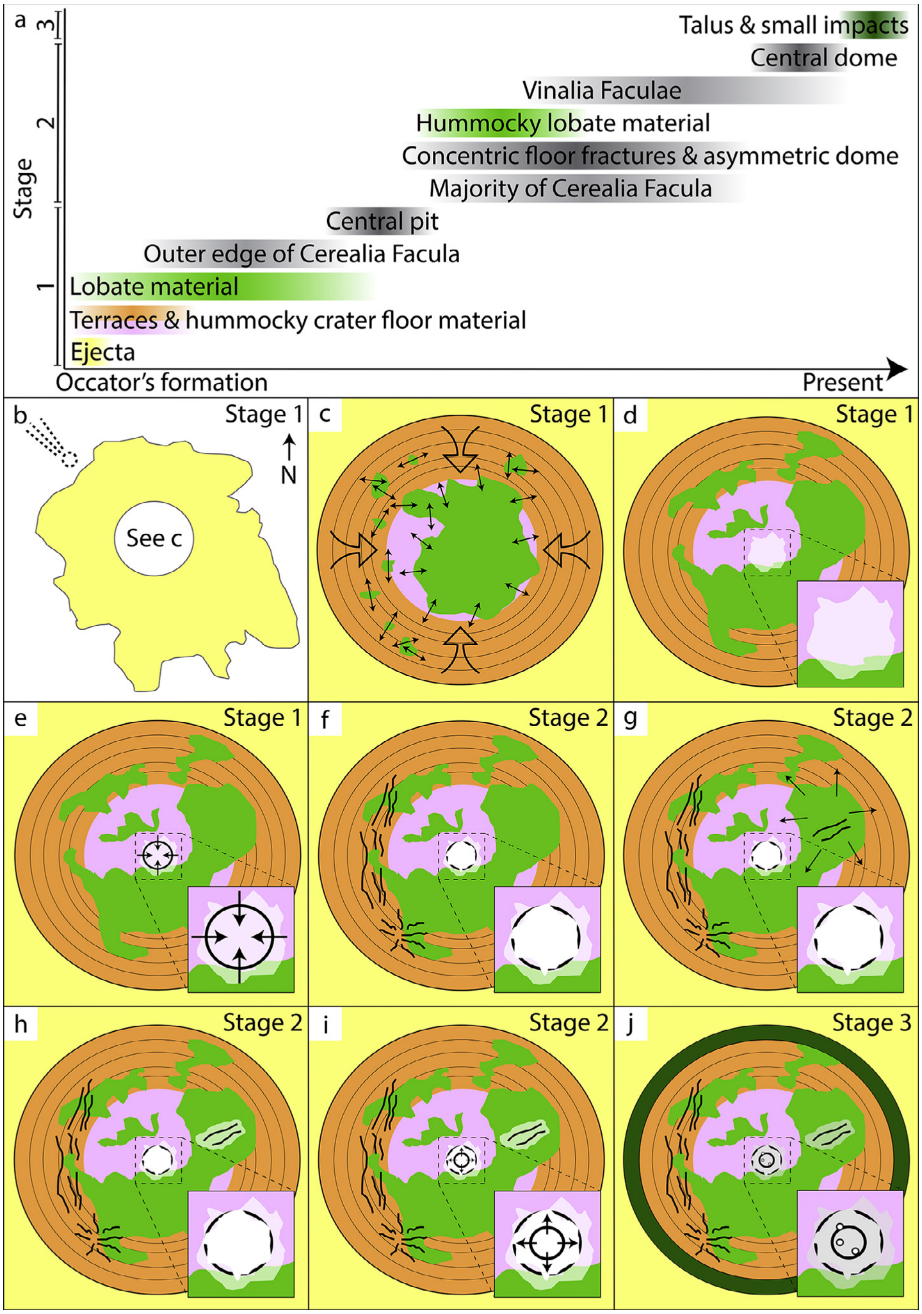


**Fig. 3.** The events that formed Occator crater and the faculae. (a) The timeline schematically illustrates the order of events that form stages 1, 2 and 3, and how the events relate to one another in time. An event was not necessarily continuous throughout an entire bar and the length of a bar is not intended to precisely represent the duration of an event. (b) In all panels Occator crater is displayed in plan view and north is to the top. Stage 1: the Occator-forming impactor (dashed lines) originated to the northwest and impacted at a slightly oblique angle, as evidenced by the distribution of the ejecta (colored yellow) (see Section 3.2.1). (c) Stage 1: terraces (colored orange) and hummocky crater floor material (colored pink) were formed by crater-wall collapse and mass wasting during and shortly after crater formation (see Section 3.2.2). During this early phase of crater formation, the lobate material (colored green) flowed around the crater interior, superposing parts of the crater terrace material and hummocky crater floor material before solidifying in place (see Section 3.2.3). Large, hollow arrows represent the collapse of the terraces and small, solid arrows represent the flow of the lobate material. (d) Stage 1: the outer, diffuse edge of Cerealia Facula (colored partially transparent white) was emplaced shortly after the Occator-forming impact, either by impact-induced hydrothermal brine deposition or by salt-rich water fountaining, perhaps sourced in a pre-existing reservoir (see Section 3.2.5). (e) Stage 1: the central pit formed after the emplacement of at least some of the lobate materials and the outer edge of Cerealia Facula, perhaps as an initial central uplift made of liquid water drained into impact-induced fractures (see Section 3.2.4). Black arrows represent the collapse of the central pit. (f) Stage 2: the majority of Cerealia Facula (colored white) is found within the central pit and thus formed after the collapse of the central pit (see Section 3.3.1). Also during this stage, it is suggested that cryomagmatic intrusions uplifted the crater floor to form concentric floor fractures (thick black lines) and an asymmetric dome, which is covered in a radial pattern of fractures (thick black lines) (see Section 3.3.2). (g) Stage 2: perhaps a further injection of material caused the inflation of the lobate materials in Occator's northeastern floor, represented by black arrows (see Section 3.3.2). The resulting stresses formed fractures in the hummocky lobate material (thick black lines). The majority of Cerealia Facula may have continued to form during this time. (h) Stage 2: brines used the fractures in the hummocky lobate material to ascend to the surface and form the Vinalia Faculae (colored partially transparent white) (see Section 3.3.3). The majority of Cerealia Facula may have continued to form during this time. (i) Stage 2: the central dome formed within the central pit (see Section 3.3.4). Black arrows represent the formation of the central dome. The central dome is covered in radiating fractures (not illustrated due to space constraints) that cross-cut the bright Cerealia Facula material. The Vinalia Faculae may have continued to form during this time. (j) Stage 3: small impact craters exposed brighter material from underneath the surface of Cerealia Facula (small white circles) and geologically recent mass wasting formed talus material (colored dark green) throughout the rim and floor (see Section 3.4.1).

Crater counts were used to derive a young age for the Cerealia Facula: ~4 Ma (Nathues et al., 2017). The young model ages of the faculae suggest the occurrence of non-impact-derived activity. The central dome displays a red slope within the Framing Camera wavelength range, while the majority of the faculae material displays a blue slope above 0.65 µm, which is interpreted to be due to an increased dark material component, rather than vacuum-decomposition of hydrated salts (Nathues et al., 2015; Bu et al., 2018). Cerealia Facula is proposed to have formed via multiple cryovolcanic extrusive events, where the extruding material is fed by brine reservoir(s) at depth that are connected by conduits to the surface.

### 2.3. *Summary of Ruesch et al.: bright carbonate surfaces on Ceres as remnants of salt-rich water fountains*

Ruesch et al. (2018a) investigate the geological processes that formed Vinalia and Cerealia Faculae through the analysis of Framing Camera images and geophysical models. The authors characterize the faculae at Occator to be composed of a bright central structure surrounded by bright mantling. The central structures at Vinalia Faculae are subtle irregular depressions (~500 m wide), whereas, at Cerealia Facula, the central structure is a dome (~400 m high and ~3000 m wide). The dome is dissected by fractures and irregular depressions. The

**Table 1**
A summary of the evidence for the driving forces behind the formation of Occator crater and the faculae being either: (1) entirely of exogenic/impact origin or (2) a combination of endogenic and impact-derived forces.

| *Feature* | *Can be explained by exogenic/impact driving force?* | *Requires combination of endogenic + impact forces?* | *Details in section* |
|---|---|---|---|
| Stage 1 | | | |
| Ejecta | Yes | Endogenic component not necessary | 3.2.1 |
| Terraces & hummocky crater floor material | Yes | Endogenic component not necessary | 3.2.2 |
| Lobate material | Yes | Endogenic component not necessary | 3.2.3 |
| Central pit | Yes | Endogenic component not necessary | 3.2.4 |
| Outer edge of Cerealia Facula | Yes | Possible with current studies | 3.2.5 |
| Stage 2 | | | |
| Majority of Cerealia Facula (besides outer edge) | Some aspects can be explained | Some aspects can be explained | 3.3.1 |
| Floor fractures & hummocky lobate material | Not with current studies | Consistent with current studies | 3.3.2 |
| Vinalia Faculae | Not with current studies | Consistent with current studies | 3.3.3 |
| Central dome | Some aspects can be explained | Some aspects can be explained | 3.3.4 |

Vinalia mantling is ~5 km in diameter, the Cerealia mantling is ~10 km in diameter, and they display sub-circular shapes around the central structures. The distribution of the mantling material is continuous close to the central structure and discontinuous, i.e., in patches, at the edges. The morphologies and morphometries of the faculae are inconsistent with impact-derived structures. While the bright material is mainly composed of endogenous carbonate particles, the prior existence of now sublimated water ice cannot be ruled out.

The authors identify three scenarios in which carbonate particles could be transported from depth to the surface to form both Cerealia and Vinalia Faculae. In the first scenario, carbonate-bearing ice is exposed at the surface, and carbonate particles are lofted by ice sublimation and deposited by fallback. However, this case fails to explain the spatial and topographic characteristics of the mantling. In the second scenario, carbonate particles are moved from depth to the surface by gases, derived, for example, by the decomposition of clathrate. In this case, the depression would correspond to the vent region formed by the high-speed ejection of gas and particles, and the mantling would correspond to the particle fallback deposit. The formation of the central dome by the same flux of particles is, however, not possible.

In the third, and most likely, scenario, a briny liquid ascends to the surface from depth. Close to, or at the surface, carbonate particles are formed by flash freezing when exposed to vacuum. The ejection of particles and water vapor (from brine evaporation) at high speed provides a way to disrupt the surface and form a vent. Mantling around the vent is formed by particle fallback. This process can be described as salt-rich water pluming or fountaining. Dome build-up can be explained by the extrusion of the same brine, if its viscosity has increased. This rheological change can occur by cooling during ascent, as well as by carapace formation at the surface. The age of the faculae, estimated to be several million years (Nathues et al., 2018), corresponds to the time of briny liquid exposure on Ceres' surface and indicates that such processes occurred in the geologically recent past.

### *2.4. Summary of Buczkowski et al.: tectonic analysis of fracturing associated with Occator crater*

Buczkowski et al. (2018a) present a tectonic analysis of the sets of fractures associated with Occator crater, and hypothesize a formation mechanism for each set. There is an extensive set of concentric fractures around Occator's central pit, as well as a smaller number of radial fractures (Fig. 2). Buczkowski et al. find that every potential method of pit formation would result in radial extensional stresses, which could trigger the concentric fracturing. Additionally, small-scale fractures are identified high on the crater wall, circumferential (but interior) to the crater rim. Their orientation and location suggest that they may have formed during the collapse of the transient crater, but without any accompanying displacement of the wall material.

Longer concentric fractures are found at the base of the crater wall (Fig. 1). Their orientation is similar to lunar Class 1 floor-fractured craters (FFCs), which are theorized to have undergone piston-like uplift of the crater floor as the last stage of magmatic intrusion beneath the crater (Jozwiak et al., 2015), suggesting that Occator could have experienced a similar intrusion, although cryomagmatic in nature. Moreover, a pattern of fractures consistent with formation due to asymmetrical domal uplift (e.g. Sims et al., 2013) is found at the southwest base of Occator's wall, in association with the concentric floor fractures (Fig. 1). In lunar FFCs, magma can utilize the concentric floor fractures to travel to the surface (Jozwiak et al., 2015). It is possible that a similar occurrence on Ceres resulted in a localized doming event, with the upwelling material being cryomagma (Buczkowski et al., 2016).

In the northeast of the crater floor, linear fractures cross the high-standing hummocky lobate material, which has a ropey surface texture. This material is analogous to terrestrial inflated viscous lava flows, and Buczkowski et al. suggest that this hummocky lobate material (Fig. 1) was inflated/uplifted via sustained injection of cryomagma from below. Fracturing occurs at the highest points of the material, suggesting that the fractures formed due to bending stresses as the material/floor was uplifted. The fractures are associated with the sodium-carbonate-bearing Vinalia Faculae, similar to the association of pyroclastic deposits and fractures in lunar FFCs (Jozwiak et al., 2015), suggesting that cryomagmatic fluids, rich in sodium carbonate, utilized the fractures to reach the surface.

There is also a set of linear fractures within Occator's floor, which occur between the southwestern wall fracture set and the central pit. It is possible that these linear fractures are simply linkages of the fractures radial to the southwestern dome and the fractures radial to the central pit. Small-scale fractures circumferential to the rim of the crater are identified in Occator's ejecta blanket. Buczkowski et al. suggest that they formed when the volatile-rich Occator ejecta blanket degassed or desiccated while differentially compacting over buried topography.

### *2.5. Summary of Neesemann et al.: the various ages of Occator crater, Ceres: results of a comprehensive synthesis approach*

Neesemann et al. (2018) derived absolute model ages for Occator crater's interior lobate deposits (ILDs, which are equivalent to the previously discussed lobate materials), and for a specific part of its ejecta blanket, using a comprehensive approach during which: (i) they corrected the measured crater and area sizes for projection-related image distortions; (ii) they applied a systematic approach for defining a representative and statistically reliable crater size-frequency distribution (CSFD); and (iii) three independent crater analysts identified and measured the diameters of craters to obtain a statistically more reliable consensus result (Robbins et al., 2014). By analyzing the spatial density of the accumulated craters, the authors identified a massive ENE-WSW trending, elongated secondary crater cluster on Occator's southern ejecta blanket and on parts of its southern interior wall terraces. They interpret that this secondary crater cluster caused an earlier overestimation of Occator's model formation age of 30.51 + / − 2.12 Ma (Nathues et al., 2015), which was based on lower resolution Framing Camera data. In addition, they find a higher density of 300–600 m craters on the ILDs than previous studies, which leads the authors to interpret that a previously determined age of the ILDs (9.2 + / − 2.00 Ma) (Nathues et al., 2017) is an underestimate.

In order to derive absolute model formation ages, they applied two fundamentally different chronology models: the lunar derived chronology model (LDM) and the asteroid-flux derived chronology model (ADM) (see Hiesinger et al. 2016 and references therein for details). The LDM production function constitutes a good approximation to the measured CSFDs, which does not necessarily equate to a verification of the model itself. The absolute LDM formation ages derived for Occator's ejecta blanket and its ILDs are 21.9 ± 0.7 Ma and 18.1 ± 1.8 Ma, respectively. For the derivation of ADM formation ages, the authors created a number of model production functions (MPFs) under different impactor/crater scaling parameters for hard rock (HR) and rubbly material (RM) (Marchi et al., 2015). Depending on the used scaling parameters, they inferred absolute model formation ages of Occator's ejecta and its ILDs ranging from 1.6 + / − 0.1 to 63.7 + / − 2.0 Ma and 1.38 + / − 0.1 and 52.7 + / − 5.1 Ma, respectively. However, the authors note that the favored MPFs, and the associated model formation ages, were created by using strength values that are less accurate or improbably low ($10^5$ dyn/cm$^2$), while those created by using more probable strength values ($10^7$ dyn/cm$^2$) are shallower and a poorer approximation for the CSFD data (discussed in detail in Neesemann et al.).

### *2.6. Summary of Raponi et al.: mineralogy of Occator crater on Ceres and insight into its evolution from the properties of carbonates, phyllosilicates, and chlorides*

Raponi et al. (2018) use VIR data, in particular the spectral parameters of all the main absorption bands, the photometry and the continuum slope, to analyze the mineralogy of Occator crater. The authors developed a procedure for removing the effects of thermal emission from the spectra, because most of the absorption features of interest are located within the spectral range effected by thermal emission.

While Ceres' average surface contains Mg- and Ca-carbonates and Mg- and $NH_4$-phyllosilicates, Occator's faculae contain Na-carbonate, Al-phyllosilicates, and $NH_4$-chloride. The high spatial resolution data allow this study to unambiguously identify $NH_4Cl$. The Cerealia and Vinalia Faculae display different mineralogies and morphologies: the composition of the Vinalia Faculae displays a lower concentration of all typical components of the bright material present on Cerealia Facula, and the Vinalia Faculae display more jagged edges. There are also variations in mineralogy within Cerealia Facula, which may suggest that different depositional events occurred within this facula. The inferred grain size of the center of Cerealia Facula is smaller than the inferred grain size of the surroundings. The authors suggest that the central grains cooled comparatively more quickly, due to the central grains forming more recently than during/immediately following the Occator-forming impact. The floor materials nearer to the faculae have intermediate properties between those of the faculae and the rest of the floor, indicating a bright material deposition event that occurred prior to the formation of the faculae, which was then partially buried by lateral mixing induced by micrometeorite impacts.

The northeastern part of the ejecta blanket has a larger abundance of the average surface materials and a smaller abundance of dark material than the rest of the ejecta blanket. This is initially surprising, because the albedo of the northeastern ejecta is lower than the rest of the ejecta. This may be explained by this part of the ejecta containing a different type of dark material that has a relatively lower albedo. This part of the ejecta also has a redder slope, which can be attributed to a smaller grain size and/or a different composition. The pre-existing subsurface materials from which the northeastern ejecta were excavated could be different to the rest of the materials exposed on the surface.

### *2.7. Summary of Longobardo et al.: photometry of Ceres and Occator faculae as inferred from VIR/Dawn data*

Longobardo et al. (2018a) investigate the photometric behavior of the faculae in comparison to the average surface, using five different spectral parameters derived from VIR data: the infrared albedo, the 2.7 µm band depth, the 3.4 µm band depth, the 3.9 µm band depth, and the infrared slope. The photometric behavior of the infrared albedo of average Ceres is compatible with C-type asteroids. This study found that the faculae display the same photometric behavior as average Ceres, despite their higher albedo. This could be due to the mixing of bright and dark material (a similar behavior is also observed on dark terrains on Vesta (Longobardo et al., 2014) or can be interpreted to indicate that the faculae have a greater roughness. The 2.7 µm band depth for Ceres' average material gets deeper with increasing phase, whereas this study finds that this deepening is two times larger for the faculae. This is interpreted to be due to a lower abundance of opaque material being present within the faculae. The 3.4 µm band depth of Ceres' average material gets deeper with increasing phase, whereas the 3.9 µm is independent of phase. However, on the faculae, both bands do not change behavior with changing photometric conditions. This could imply that: (a) there is an additional carrier (other than carbonates) of the 3.4 µm band in Ceres' average material (and this could explain the different behavior with respect to the 3.9 µm band), or (b) the abundant carbonates do not produce a phase-reddening effect on the spectrum. The latter appears to be supported by the infrared slope of the faculae, which does not display phase reddening behavior, whilst the average Cerean material does.

### *2.8. Summary of Bowling et al.: post-impact thermal structure and cooling timescales of Occator crater on dwarf planet 1 Ceres*

Bowling et al. (2018) simulate the formation of Occator crater using an iSALE-2D 'Dellen' shock physics code. The target is a mixture of serpentine and water with a surface temperature of 150 K and a lithospheric temperature gradient of 0.5 K/km. Ceres' surface is assumed to have rock-like rheological properties for long-term, low/no strain rate processes (e.g. viscous relaxation) and ice-like rheological properties for high-strain rate processes (e.g. impacts). The impactor collides at 4.8 km/s. For these assumptions, a ~25 km deep transient crater is formed, which is coated with hot impactor/target material. The transient crater rapidly collapses and the hottest material is concentrated in a plug that extends to a depth of 15 km in the crater center and is also uplifted. The uplift is unstable and soon collapses, spreading hot material across the crater floor. Approximately 1000 km$^3$ of the material is heated above 273 K. In simulations where the target contains comparatively more water ice, slightly deeper craters form, with more material at temperatures of > 273 K.

Shortly after the impact, the crater floor is a mixture of hot impactor material, relatively hot target material originating from the near-surface and relatively cool material from depths in excess of 20 km. The predicted post-impact temperatures allow for the existence of hydrothermal systems of brines within the crater floor. Ponds of brines could exist in the center of the crater shortly after crater formation. Ceres' surface conditions would lead to the rapid vaporization of the brines, leaving behind salt deposits that could potentially form part of the faculae. Ballistically-driven salt deposits could also be ejected from fractures, consistent with the formation mechanism proposed for the Vinalia Faculae by Buczkowski et al. (2018a), Nathues et al. (2018), Quick et al. (2018) and Ruesch et al. (2018a).

Bowling et al. estimate that cooling would shut off hydrothermal systems within ~400 Kyr to ~4 Myr after the Occator-forming impact, depending on the thermophysical properties assumed for the crust.

Model ages indicate that the faculae are at least ~18 Myr younger than the formation age of the crater (Nathues et al., 2018; Neesemann et al., 2018). Thus, because of the discrepancy between the lifetime of hydrothermal systems (~4 Myr) and the age of the faculae versus the age of the crater (~18 Myr), Bowling et al. conclude that impact-derived hydrothermal systems could not be uniquely responsible for the formation of the faculae. However, the authors also suggest two alternative mechanisms to explain this discrepancy: (1) pre-existing, deeply buried volatile-rich materials could have been uplifted directly below the crater center by the Occator-forming impact, providing a reservoir for later, non-impact-derived brine deposition, or (2) if different properties, such as a higher geothermal gradient (>0.5 K/km), were used than in the current models, the cooling time of the crater may be extended past the current estimates.

### *2.9. Summary of Quick et al.: a possible brine reservoir beneath Occator crater: thermal and compositional evolution and formation of the Cerealia dome and Vinalia Faculae*

Quick et al. (2018) investigate the thermal and compositional evolution of a potential brine reservoir beneath Occator, which is one possible interpretation for the gravity data (A. Ermakov, personal communication; also see Ermakov et al., 2017). Excess pressures caused by gradual freezing of this reservoir, or caused by the Occator-forming impact, could have generated fractures that drove briny cryolavas to Ceres' surface in the geologically recent past. The reservoir is modeled as a mixture of chloride and sodium carbonate brines with an initial temperature of 273 K. A reservoir with similar dimensions to Occator (~90 km wide) would crystallize in ~600 Myr. Just 5% crystallization would induce excess pressures capable of driving cryolavas to the surface from depths of up to ~150 km. Additionally, briny cryomagmas at 266 K could be driven from 45 km deep with less than 1.6% reservoir crystallization. The authors find that major delivery of chloride-bearing fluids to the surface would cease by ~35 Myr, and, by ~300 Myr, the reservoir would contain too many crystals (~50%) to facilitate continued surface eruptions. For a larger reservoir, ~200 km in diameter, cooling would take ~3 Gyr, eruptions of briny cryomagmas would cease after ~1.6 Gyr of reservoir cooling and eruptions of chloride-bearing fluids would cease by ~170 Myr of cooling. Also, if fluids with sodium carbonates as their primary low eutectic contaminant have endogenic origins, they likely originated in crustal reservoirs located at depths shallower than 35 km, because the bulk temperature at the time the reservoir reached 1.6% crystallization is found to be 266 K.

Assuming cryomagmas traveled to the surface in 10-m-wide fractures, and that $NH_3$-rich cryomagmas would have the lowest freezing temperatures of all solutions in the reservoir, Quick et al. found that in order to reach the surface at warm enough temperatures to erupt (>176 K), cryomagmas must have viscosities ≤ $10^7$ Pa s, and fractures must propagate at speeds ≥ $10^{-5}$ m/s.

Owing to Ceres' low gravity, the Vinalia Faculae could have been ballistically emplaced by eruptions driven by < 1 wt% $CO_2$, $CH_4$, $NH_3$, $SO_2$ and/or $H_2O$ vapor, while the diffuse edges of Cerealia Facula could have been ballistically emplaced by < 2 wt% of any of the aforementioned driving volatiles. Once cryolavas erupt at Ceres' surface, they would boil violently for just over 3 months until an icy crust develops. This crust would serve as an insulator for the underlying cryolavas, allowing effusive flow. Quick et al. find that if emplaced similarly to Ahuna Mons, the Cerealia dome was likely formed by cryolavas with bulk kinematic viscosities on the order of $10^6$ $-10^8$ $m^2/s$. Corresponding times to form the dome range from a few days to just over 9 months. Note that the cryolava viscosities required to form the Cerealia dome would be somewhat lower than those reported in Ruesch et al. (2016) for the emplacement of Ahuna Mons.

In comparison to icy satellites like Europa, an order of magnitude less of reservoir crystallization is required on Ceres to drive fluids from comparable depths (cf. Fagents, 2003). In addition, the density of Ceres' crust (~1300 $kg/m^3$) is higher than the density of several individual briny solutions that may serve as cryomagmas on the dwarf planet (a NaCl hydrate briny solution is ~ 1200 $kg/m^3$). Cryovolcanism may have therefore been more easily initiated on Ceres than on the icy satellites in the geologically recent past.

### *2.10. Summary of Bu et al.: stability of hydrated carbonates on Ceres*

Hydrated salts, particularly natron (hydrated sodium carbonate), are expected to have formed deep within Ceres before surficial emplacement (Zolotov, 2017). However, VIR measurements of Occator's faculae detect no water signature (e.g. Raponi et al., 2018), likely due to dehydration in Ceres' low-pressure environment. Experimental evidence implies natron is highly stable at < 130 K (McCord et al., 2001), while thermodynamic models (Zolotov, 2017) suggest dehydration of aqueous salts at pressures and temperatures (~160–240 K) equivalent to Ceres' equator and mid-latitudes. To measure dehydration rate and its temperature dependence, Bu et al. (2018) systematically studied the stability and consequent spectral effects of hydrated and anhydrous sodium carbonates exposed to low pressure at Ceres' cryogenic temperatures by UV–Vis-NIR reflectance spectroscopy and X-ray diffraction analysis.

Bu et al. show that for natron and other hydrated sodium carbonates, $H_2O$-loss begins simultaneously with vacuum-exposure at 122, 200, and 240 K. Without a continuous hydration source, the water absorption features in natron reduce to < 2%, below VIR's detection level, within < 6 days at 200/240 K, making it unlikely that hydrous sodium carbonate would be detected at Ceres' equator and mid-latitudes (Tosi et al., 2015; Formisano et al., 2016). Definitive observation of hydrated sodium carbonate would indicate surficial water or newly deposited material transported quickly from the sub-surface, perhaps in a mechanism similar to that suggested by Ruesch et al. (2018a). While unlikely, if hydrous sodium carbonate were detected in Ceres' mid-latitudinal region, the position of the 1.9-μm water-absorption feature could be used to determine the hydration state and the deposit age. At Ceres' polar-regions (~122 K), dehydration is slower, with hydrated sodium carbonate retaining a detectable water-signature for ~300 years. In this case, age could be approximated by the dehydration rate derived from an Avrami model by Bu et al.

For the NIR, dehydration results in reduction of the blue spectral slope, brightening at > 1.4 μm and attenuation of $H_2O$ absorption features. For the visible, dehydration and extended vacuum exposure result in no significant (<10%) spectral changes. Thus, vacuum exposure of sodium carbonates alone cannot account for Cerealia Facula's visible red slope observed by Dawn's Framing Camera (Nathues et al., 2017), nor can dehydration of sodium carbonate explain the progressive change in slope between dome center and crater background (Nathues et al., 2015). In the UV, extended low-pressure exposure of sodium carbonates results in enhanced attenuation, with the UV absorption edge shifting toward longer wavelengths, better matched, but not identical, to Ceres' unusual UV–visible spectral slope (Li et al., 2006; Hendrix et al., 2016). New absorptions also evolve at 235 and 275-nm, attributable to electronic transitions that develop with increasing vacuum-induced local defects. The 275-nm absorption observed in natron/natrite with extended vacuum-exposure may be a factor in the ~280 nm feature observed in broad-band HST spectra of Ceres (Li et al., 2006).

### *2.11. Summary of Thomas et al.: kinetic effect on the freezing of ammonium-sodium-carbonate-chloride brines and implications for the origin of Ceres' bright spots*

The experimental work of Thomas et al. (2018) is motivated by the recent suggestion that the bright deposits of Occator crater, comprised of natrite ($Na_2CO_3$) and $NH_4Cl$ or $NH_4HCO_3$ (De Sanctis et al., 2016), originate from freezing of brines as they reach the surface from an internal reservoir. Previous work examined the freezing of putative subsurface brines containing ammonium, sodium, carbonate, and chloride ions, and found support for this hypothesis (Vu et al., 2017). Here, Thomas et al. investigate this hypothesis further by examining the effect of freezing rate on the formation of minerals on Ceres' surface.

Using infrared and Raman spectroscopies, flash frozen brines are found to form predominantly ammonium chloride and ammonium bicarbonate, even in the case of sodium-dominated solutions. Moreover, natrite is formed from every freezing scenario regardless of freezing rate and relative ionic concentrations, which is consistent with the observed composition of Occator's faculae by Dawn (De Sanctis et al., 2016; Raponi et al., 2018). In contrast, hydrohalite ($NaCl•2H_2O$) is only seen to form from solutions with an excess of sodium and/or chloride ions. By comparing the observable products upon fast (kinetic) and slow (thermodynamic) freezing, constraints can be placed on the freezing rate and composition of brines that lead to the minerals seen in Occator crater. For example, the presence of $NaHCO_3$ indicates thermodynamic (slow) freezing of a brine that is equimolar in sodium and ammonium, while the presence of ammonium salts implies kinetic freezing of such a brine. This work shows that slow-freezing (30 K/min or less) is most compatible with the observed composition of Occator's faculae. In combination with the other studies in this special issue, this work indicates that the brine-forming materials were most likely derived from at least a few kilometers within Ceres and were mobilized either by a cryovolcanic process or by the Occator-forming impact, and not by direct excavation.

### *2.12. Summary of Schenk et al.: the central pit and dome at Cerealia Facula bright deposit and floor deposits in Occator crater, Ceres: morphology, comparisons and formation*

Schenk et al. (2018) find the texture of Occator's lobate materials, and their sometimes steep, few-hundred-meter high lobate margins, are analogous to impact melt sheets within lunar craters. These, and additional observations, lead them to propose that Occator's lobate materials are an impact melt sheet composed of melted water ice, fragmented, unmelted debris and dissolved salts. Degraded examples of lobate materials are identified in Dantu and Ikapati craters.

Occator's central pit ($\sim$9–10 km wide, $\sim$1 km deep) is covered by Cerealia Facula bright material, and the outer parts of the central pit contain tendrils of bright material (Fig. 2). A fainter ring of bright material extends 5–10 km from the margin of the central pit into the crater floor. There are dark mounds within Cerealia Facula and bright material on top of a $\sim$2 km high plateau, possibly formed by ballistic 'airfall' emplacement, by uplift of blocks or by discrete bright material sources. The authors propose hydrothermal fluids flowed out of fractures along the walls of the central pit into the interior, flowing around topographic obstacles formed by the dark mounds. Evaporation of the fluids formed the tendrils and the central region of bright material. The $\sim$2 km wide and $\sim$700 m high central dome is within the central pit. The bright material on the top of the dome is cut by fractures, indicating the central dome formed after emplacement of the Cerealia Facula bright material. The authors propose the central dome was uplifted via laccolithic intrusion or volume expansion from freezing of a central reservoir of volatiles long after the Occator-forming impact. The lack of a termination scarp at the edge of the central dome is proposed to indicate that it was inflated from below rather than being an extrusive feature.

Schenk et al. identify $\sim$11 central pit craters on Ceres, which are more degraded than Occator's central pit and do not contain a central dome, indicating that central domes may be fragile structures that degrade easily. Central pit craters are not found in Ceres' cooler polar regions and are also not found on colder icy moons of the outer Solar System, leading the authors to propose that temperature strongly controls central pit formation. Schenk et al. conclude that the 'melted uplift model' (e.g. Croft, 1981; Senft and Stewart, 2011; Bray et al., 2012) is most likely to have formed Cerean central pit craters, but note that, at present, no one model can completely explain all observations. In the 'melted uplift model' model, an initial liquid water central uplift drains into impact-induced fractures, leaving a central pit. It is more difficult to definitively evaluate which model formed central pit craters on Ganymede and Callisto, because there is no high-resolution imaging comparable to the Dawn dataset for those bodies.

### *2.13. Summary of Stein et al.: the formation and evolution of bright spots on Ceres*

Stein et al. (2018) investigate the hundreds of faculae that are spread across Ceres' surface. While none are as bright as the Cerealia Facula and Vinalia Faculae (the Bond albedos of the global faculae range from $\sim$0.02 to $<$ 0.5), understanding these other faculae provides context for our investigation of Occator's faculae. The authors use Framing Camera data to classify, identify and map these globally distributed faculae into four geologic classes: (1) floor faculae, which occur within crater pits, peaks or floor fractures (including Cerealia Facula and Vinalia Faculae), (2) rim/wall faculae, which occur on crater rims or walls, (3) bright ejecta blankets and (4) Ahuna Mons.

The floor faculae occur in young, large and deep craters that often contain other morphological evidence for upwelling and degassing of volatiles, such as pitted terrains. Impact-induced heating and upwelling of subsurface volatiles, and/or upwelling of extant brines through impact-induced fractures, and/or upwelling of brines as low-density plumes, could form the floor faculae. Their association with impact craters makes the first and/or second possibilities likely. Lateral variations in subsurface ice/brines, composition and temperature may result in floor faculae being formed in only select regions of Ceres.

The rim/wall faculae and bright ejecta blankets occur in and around young craters of a variety of sizes. Both are thought to form as previously emplaced faculae materials, originally formed either via spatially heterogeneous subsurface processes or as floor faculae, are excavated by impacts. Modeling suggests that such burial of previously exposed faculae by impact-induced lateral mixing and subsequent excavation could occur on timescales of less than several hundreds of millions of years, which is consistent with the ages of the host craters of the rim/wall faculae and the bright ejecta blankets. Faculae are found to darken over time, likely due to combined effects of space weathering and impact-induced lateral mixing, and are destroyed on timescales of $<$ 1.25 Ga. Warmer subsurface temperatures and higher impact rates during Ceres' earlier history suggest that faculae formation would have occurred more frequently in the geologically distant past.

### *2.14. Summary of Palomba et al.: compositional differences among bright spots on the Ceres surface*

Palomba et al. (2018) use data from the VIR instrument to catalog all of the bright spots on Ceres' surface, including the Cerealia Facula and Vinalia Faculae, and analyze their compositional properties, thus providing context for our analysis of Occator's faculae. Similarly to Stein et al. (2018), 90% of the catalogued bright spots occur in the ejecta of impact craters, or in the crater rims, walls or floors. The authors also find that bright spots are somewhat concentrated within the younger of Ceres' terrains.

The bright spots are divided into four families. The first family contains the majority of the bright spots. These are similar to Ceres' average surface because they have a lower reflectance than the other bright spots, are composed of Mg-phyllosilicates and ammoniated clays and do not contain high abundances of Mg- and Ca-carbonates. This is in contrast to the Cerealia Facula and Vinalia Faculae family, which contain unusually high abundances of Na-carbonates and Al-phyllosilicates. Cerealia Facula has a stronger carbonate band and a weaker OH band in comparison to the Vinalia Faculae. Oxo-type bright spots are depleted in phyllosilicates and have a high to moderate albedo. Their carbonate band strength is similar to that of the Vinalia Faculae. Finally, the family of bright spots that contains Haulani, Ernutet and Kupalo craters is moderately rich in carbonates and slightly depleted in Mg-phyllosilicates and ammoniated phyllosilicates.

The authors propose that the four families of bright spots represent an evolutionary path in albedo and composition followed by Cerean bright spots. When they are very fresh, bright spots are similar to the Cerealia Facula and Vinalia Faculae. Later, the volatilization of OH, combined with minimal mixing with surrounding materials, produces Oxo-type bright spots. More extensive mixing produces Haulani/Ernutet/Kupalo-type bright spots, before additional mixing results in the last evolutionary step being reached: the formation of bright spots of the most common type.

## 3. Synthesis

### 3.1. Overview

Each of the studies in this special issue provides key pieces of evidence that allow us to identify the driving forces behind the formation of Occator crater and its faculae. Based on these studies, we propose that the following sequence of events led to the formation of Occator, Cerealia Facula and Vinalia Faculae. We divide these events into stages 1 to 3. The stages are sequential: stage 1 occurred before stage 2, and stage 2 occurred before stage 3 (Fig. 3a). However, the events discussed within a stage are not necessarily sequential, unless specific age relationships between them are noted.

### 3.2. Stage 1 of Occator and faculae formation

#### 3.2.1. Ejecta

The distribution of Occator's ejecta indicates that the Occator-forming impactor originated to the northwest and impacted at a slightly oblique angle of ∼30–45°, perhaps closer to ∼30° (Scully et al., 2018b) (Fig. 3b). Some ejecta rays travel for ∼500 km (Nathues et al., 2018). The northeastern part of the ejecta blanket and crater interior has a relatively lower albedo. Raponi et al. (2018) find that this part of the ejecta contains a smaller amount of dark material than the average surface, indicating that it is composed of a different type of dark material with an even lower albedo. It also has a comparatively smaller grain size, suggesting a different composition. It is possible that the source material for this northeastern ejecta is uniquely located in the subsurface to Occator's east, or it may be more deeply buried, and inaccessible by the Occator-forming impact, in the subsurface to Occator's west (Nathues et al., 2018; Scully et al., 2018b; Raponi et al., 2018).

#### 3.2.2. Terraces and hummocky crater floor material

The Occator-forming impactor is sufficiently large and energetic to form a complex crater. During and immediately following the crater formation process, terraces and hummocky crater floor material are formed by crater-wall collapse and mass wasting, respectively (Fig. 3c). Scully et al. (2018b) propose that when sets of collapsing terraces converge, ∼90° bends are formed in the crater rim. Small-scale fractures circumferential to the crater rim in Occator's interior are also proposed to form during the collapse of the transient crater (Buczkowski et al., 2018a).

Other complex craters on Hanami Planum also share the aforementioned features, but Occator is the largest and youngest of these craters (e.g. Buczkowski et al., 2018b; Scully et al., 2018b). The features that make Occator crater unique are the Cerealia Facula, Vinalia Faculae and the lobate materials: Cerealia and Vinalia Faculae are the brightest of the bright materials scattered across Ceres' surface (Palomba et al., 2018; Stein et al., 2018) (see Section 3.4.1), and the lobate materials are the most extensive and least degraded floor materials in any Cerean crater (Schenk et al., 2018).

#### 3.2.3. Lobate material

Schenk et al. (2018) find that Occator's lobate materials are analogous to impact melt sheets in lunar craters. Through simulations of the Occator-forming impact, Bowling et al. (2018) predict that impact-induced heating could not melt silicates, but that ∼1000 $km^3$ of material could be heated sufficiently for water ice to melt and for most salts to go into solution (see also Zolotov, 2017). Scully et al. (2018b) find that the volume of the lobate material is ∼20–200 $km^3$, which is a fraction of the material heated above the melting point of water in the Bowling et al. simulations. Thus, it is proposed that the lobate materials are a slurry of impact-melted water, salts in solution and particulates/boulders of unmelted silicates and salts. Shortly after the crater's formation, this impact slurry flowed around the crater interior, superposing parts of the crater terrace material and hummocky crater floor material before solidifying in place (Bowling et al., 2018; Schenk et al., 2018; Scully et al., 2018b) (Fig. 3c and d). Scully et al. (2018b) propose that the texture of the lobate materials (knobby or smooth) depends on whether the lobate material entrains or does not entrain blocks, respectively. The impact slurry interpretation is consistent with the lunar derived chronology model ages found by Neesemann et al. (2018) for Occator's ejecta and lobate materials, which are essentially contemporaneous: ∼22 Ma and ∼18 Ma, respectively. Alternatively, the lobate materials are proposed to be a debris avalanche deposit from collapse of the southeastern crater wall (Nathues et al., 2018), which is consistent with model ages for Occator and the lobate materials derived by Nathues et al. (2017): ∼31 Ma and ∼9 Ma, respectively.

#### 3.2.4. Central pit

Occator contains a central pit, is the least degraded of the ∼11 Cerean central pit craters, and was also formed shortly after the initial formation of Occator crater (Schenk et al., 2018). There is a set of concentric fractures surrounding the central pit, which likely formed as the pit collapsed. Some of these fractures are located within the lobate materials, indicating that at least portions of the lobate materials were solidified prior to the formation of the central pit (Buczkowski et al., 2018a; Schenk et al., 2018; Scully et al., 2018b). Of the previously proposed mechanisms of central pit formation, Schenk et al. (2018) conclude that the 'melted uplift model' (e.g. Croft, 1981; Senft and Stewart, 2011; Bray et al., 2012) is the most likely to have formed Occator's central pit. In this model, an initial central uplift made of liquid water drains into impact-induced fractures, leaving a central pit instead of a central peak (Fig. 3e).

#### 3.2.5. Outer edge of Cerealia Facula

The outer edge of Cerealia Facula, which is mostly located outside of the central pit, is composed of a 5–10 km wide faint ring of bright material (Schenk et al., 2018; Ruesch et al., 2018a). This is a discontinuous deposit of bright material that is distinctly diffuse in comparison to the rest of Cerealia Facula (Scully et al., 2018b). Parts of the outer edge are cross-cut by the concentric fractures surrounding the central pit (Buczkowski et al., 2018a; Schenk et al., 2018; Scully et al., 2018b), indicating that emplacement of the outer edge occurred early in Occator's history. Raponi et al. (2018) find that the faculae contain sodium carbonate, ammonium chloride and Al-phyllosilicates. Zolotov (2017) shows that sodium carbonate can be concentrated in a water-rich, impact-induced melt reservoir, and later precipitate out to form the faculae deposits. Bowling et al. (2018) find that conditions shortly after the Occator-forming impact would allow for impact-induced hydrothermal circulation and brine deposition. Upon reaching the surface, the brines would vaporize, leaving behind a bright residue of salts and thus forming the faculae (e.g. Bowling et al., 2018; Ruesch et al., 2018a). This is consistent with the rapid rate of dehydration measured for hydrous sodium carbonates (e.g. natron) with exposure to vacuum at Ceres' relevant temperatures (e.g. Bu et al., 2018), which accounts for the detection of only anhydrous sodium carbonate and non-detection of ice by VIR. Alternatively, it is also possible that this part of Cerealia Facula could have been emplaced via a mechanism such as salt-rich water fountaining (Ruesch et al., 2018a). The study of Quick et al. (2018) finds that < 2 wt% volatiles, perhaps sourced in a pre-existing reservoir, could drive ballistic eruptions that would form diffuse deposits such as the outer edge of Cerealia Facula. No matter the mechanism, this part of Cerealia Facula was likely emplaced shortly after the Occator-forming impact because of the aforementioned cross-cutting relationship observed with the concentric fractures (Fig. 3d and e).

Raponi et al. (2018) find that the crater floor materials near the faculae have intermediate properties between the mineralogy of the faculae and the rest of the crater floor. These intermediate parts of the crater floor may have become less distinctly bright over time through partial burial and lateral mixing induced by micrometeorite impacts. Thus, these parts of the crater floor may be instances of brine deposition that are older than the outer edge of Cerealia Facula.

### 3.3. Stage 2 of Occator and faculae formation

#### 3.3.1. Majority of Cerealia Facula (besides outer edge)

The majority of Cerealia Facula is composed of a roughly circular deposit of bright material. It has a continuous appearance in comparison to the diffuse material that makes up Cerealia Facula's outer edge (Ruesch et al., 2018a; Scully et al., 2018b). The lower region of the central pit is entirely covered by the continuous Cerealia Facula bright material. Tendrils of the bright material are located on the walls of the central pit (Schenk et al., 2018). Photometric properties of the faculae indicate that they have a greater roughness and/or lower abundance of opaque material than the rest of the crater floor (Longobardo et al., 2018a). Thomas et al. (2018) find that natrite ($Na_2CO_3$) is formed regardless of the freezing rate of the faculae-forming materials, which is consistent with the observed composition of Occator's faculae (De Sanctis et al., 2016; Longobardo et al., 2018b; Raponi et al., 2018). Raponi et al. (2018) identify variations in mineralogy across Cerealia Facula, which suggest that the facula was formed by different depositional events. Schenk et al. (2018) propose that brines flow out of fractures along the walls of the central pit, forming the bright tendrils on the walls, and accumulate in the central region, forming the central continuous bright material (Fig. 3f). The bright-material-forming fluids appear to have flowed around the dark mounds within Cerealia Facula (Schenk et al., 2018) and the build-up of multiple flows likely formed the central continuous portion of Cerealia Facula.

The model ages of Occator crater indicate that the faculae are a few millions of years old, ~4 Myr for Cerealia Facula and perhaps < 2 Myr for Vinalia Faculae (Nathues et al., 2017; Nathues et al., 2018), while the crater itself is older: ~22 Ma (Neesemann et al., 2018) or ~34 Ma (Nathues et al., 2015; Nathues et al., 2017; Nathues et al., 2018). Schenk et al. (2018) note that it is difficult to determine the exact time interval between the formation of the faculae and Occator because: (i) the faculae may have different mechanical properties than the rest of Occator's floor, on account of their different composition, and (ii) their small area means that stochastic variability in crater density could have a pronounced effect. However, it has not been demonstrated that these factors can completely account for the age discrepancy between the faculae and Occator. In addition, the inferred grain size of the center of Cerealia Facula is finer than the rest of Occator's floor, which indicates that the center of Cerealia Facula cooled comparatively more rapidly. More rapid cooling is consistent with the center of Cerealia Facula forming after the dissipation of impact-induced heat (Raponi et al., 2018). Thus, the aforementioned lines of evidence suggest that the majority of Cerealia Facula formed later, at least ~18 Myr, than Occator crater (based on faculae ages derived by Nathues et al. 2018 and a crater age derived by Neesemann et al. 2018). However, the Bowling et al. (2018) simulations predict that impact-induced hydrothermal systems can only occur within ~400 Kyr to ~4 Myr of the impact. Therefore, the age gap between the formation time of the majority of Cerealia Facula and the lifetime of hydrothermal systems suggests that additional driving forces control the formation of the majority of Cerealia Facula.

As discussed in the introductory paper to this special issue (Scully et al., 2018a), pockets of briny liquid, relict pieces of Ceres' ancient ocean, could be preserved within Ceres' present-day subsurface (Castillo-Rogez and McCord, 2010; Neveu and Desch, 2015; Travis et al., 2017; Castillo-Rogez et al., 2018). Pre-existing, deeply buried volatile-rich materials could have been uplifted directly underneath the center of Occator by the crater-forming impact, which could provide a reservoir for later, non-impact-derived brine deposition (Bowling et al., 2018). Alternatively, fractures formed by the gradual crystallization of a pre-existing reservoir could also have allowed brines to reach the surface (Quick et al., 2018). A number of studies within this special issue investigated whether a reservoir of briny liquid, existing within Hanami Planum prior to the Occator-forming impact, could have been the driving force behind the formation of the majority of Cerealia Facula. Assuming that there is a briny liquid reservoir in Hanami Planum, underneath Occator crater, Quick et al. (2018) find that it is relatively easy to drive reservoir material to the surface: gradual freezing of a chloride/carbonate brine reservoir can form fractures and drive brines to the surface. This process could also be aided by impact-induced fracturing. For example, in the early stages of crystallization in a reservoir the size of Occator (~90 km across), only 1.6% crystallization could drive brines at 266 K to the surface from depths of ~45 km. Smaller reservoirs are also possible, and could drive brines to the surface for shorter periods of time. If brines were driven to the surface through 10 m wide fractures, they would need to have viscosities of $\leq 10^7$ Pa s and propagation speeds of $\geq 10^{-5}$ m/s to reach the surface at warm enough temperatures to erupt (> 176 K). On the surface, such briny materials would boil for ~3.5 months before the formation of an icy crust. A developing crust of ice would insulate the materials and facilitate effusive flow before final solidification of the bright deposits. The ice would eventually be lost via sublimation. Alternatively, deposition of brines during this initial boiling phase or sublimation of the icy crust sometime after emplacement of the briny flow could leave bright deposits behind.

In addition, Ruesch et al. (2018a) investigate different mechanisms for the transport of carbonate particles from within Ceres to the surface. In their favored scenario, a briny liquid ascends to the surface and is emplaced via salt-rich water fountaining. Particle ejection and high-speed water vapor form a central vent, while flash freezing forms the carbonate particles, which mantle the area around the vent after fallback. Nathues et al. (2018) also suggest that brine reservoirs at depth, connected to the surface via conduits, fed multiple extrusive events that formed the Cerealia Facula.

There are also geochemical constraints on the formation of the faculae to consider: sodium carbonate and ammonium chloride are predicted to precipitate out of an ancient ocean early in Ceres' history, and the majority are thought to be in the crust today (Castillo-Rogez et al., 2018; Neveu and Desch, 2015). Thus, briny relict ocean liquid is predicted to be dominantly composed of residual sodium chlorides, potassium chlorides and ammonia (Neveu and Desch, 2015; Castillo-Rogez et al., 2018), which is inconsistent with the dominantly sodium carbonate and ammonium chloride composition of the faculae (e.g. Raponi et al., 2018). It is possible that xenoliths of sodium-carbonate/ammonium-chloride-rich crust could become entrained in the briny relict ocean liquid as it moved rapidly towards the surface via fractures, similar to the proposition that xenoliths could be entrained in rising cryomagmas on Enceladus (Fortes et al., 2007). However, whether such a process could occur on Ceres will be the focus of future work.

While studies in this special issue do demonstrate that it is possible to transport the faculae-forming materials to the surface from a relict briny reservoir (e.g. Quick et al., 2018; Ruesch et al., 2018a), there may be difficulties reconciling the aforementioned geochemical constraints with a pre-existing reservoir of briny relict ocean. As an alternative formation mechanism, it is possible that all of Cerealia Facula was formed from an impact-induced hydrothermal system, which is one possible formation mechanism of the Cerealia Facula's outer edge (see Section 3.2.5). In order for this to be the case, however, the differences in duration between the predicted lifetime of a hydrothermal system (~400 Kyr to ~4 Myr after the impact) (Bowling et al., 2018) and the age gap between the formation of the majority of Cerealia Facula and Occator crater (at least ~18 Myr) (see Nathues et al. (2018), Neesemann et al. (2018) and references therein) must be explained. Models have begun to explore a range of possible crustal thermophysical properties and thermal gradients, in order to assess (i) whether the predicted lifetime of the hydrothermal system may be extended and (ii) whether a connection could be formed between a shallow, impact-induced reservoir and a deeper, pre-existing reservoir of briny relict liquid (e.g. Hesse and Castillo-Rogez, 2018).

#### 3.3.2. Floor fractures and hummocky lobate material

Buczkowski et al. (2018a) find that long concentric fractures around the base of Occator's wall make Occator crater analogous to Class 1 lunar floor-fractured craters (Fig. 3f). Magmatic intrusion below lunar floor-fractured craters is thought to uplift the crater floor in a piston-like motion, forming the concentric fractures. On Ceres, Buczkowski et al. (2018a) suggest that a cryomagmatic intrusion was the driving force behind the floor-fracturing process. An alternative possibility is also beginning to be investigated: solid-state flow, instead of cryomagmatic intrusion, may have formed some of the floor-fractured craters on Ceres (Buczkowski et al., 2018c; Bland et al., 2018).

In order for the floor fractures to form via the cryomagmatic intrusion hypothesis, the cryomagmatic intrusion must be trapped vertically and horizontally by the broken material underneath the crater; as the trapped intrusion is fed from an underlying reservoir, it domes, uplifting and fracturing the overlying, brittle crater floor (Buczkowski et al., 2018a). A pre-existing reservoir of briny relict ocean liquid could provide the source material to form the cryomagmatic intrusion, and to feed it when it became trapped, because as the overburden pressure was released by the formation of Occator crater, the reservoir material would move upwards. Crystallization of the reservoir could also contribute to moving the reservoir material upwards into the trapped cryomagmatic intrusion (Quick et al., 2018). Buczkowski et al. (2018a) propose that some of these floor fractures formed a conduit via which the cryomagma upwelled underneath the floor of Occator, forming the asymmetric dome in Occator's south-western floor.

The lobate material in the northeast of Occator's floor has a distinctly hummocky texture and is ~160 m higher than the rest of the lobate materials (Buczkowski et al., 2018a; Scully et al., 2018b). The morphology of the hummocky lobate material is analogous to terrestrial inflated viscous lava flows, which are inflated/uplifted after the surface cools but the interior liquid volume increases via high effusion rates and sustained injection from below (Buczkowski et al., 2018a). It is possible that another instance of injection of material from the pre-existing reservoir of briny relict ocean liquid caused the inflation of the lobate materials in Occator's northeastern floor (Fig. 3g). Before the injection, this lobate material was likely smooth or knobby in texture (see Section 3.2.3), but after injection it gained its hummocky surface texture.

#### 3.3.3. Vinalia Faculae

As the hummocky lobate material was uplifted (see Section 3.3.2), bending stresses were induced in the material, which formed fractures at the highest points (Buczkowski et al., 2018a). The Vinalia Faculae are associated with this set of fractures (Buczkowski et al., 2018a; Nathues et al., 2018; Ruesch et al., 2018a; Schenk et al., 2018; Scully et al., 2018b). Within the center of many of the diffuse Vinalia Faculae deposits are ~500 m wide irregular depressions, which are morphologically inconsistent with impact craters. The diffuse mantling deposits surround the Vinalia Faculae for up to ~5 km (Ruesch et al., 2018a). It is likely that brines used the fractures to ascend to the surface and form the Vinalia Faculae (Buczkowski et al., 2018a; Nathues et al., 2018; Quick et al., 2018; Ruesch et al., 2018a) via a mechanism such as salt-rich water fountaining (Ruesch et al., 2018a) (Fig. 3h), which is also a possible formation mechanism of the outer edge of Cerealia Facula (see Section 3.2.5). Ceres' low gravity makes it easy for such ballistic eruptions to occur on the surface: less than 1 wt% volatiles could drive ballistic eruptions to form the Vinalia Faculae (Quick et al., 2018). The Vinalia Faculae have a lower concentration of all the compositional components observed in majority of Cerealia Facula (Raponi et al., 2018), perhaps indicating that they formed over a less prolonged timespan.

#### 3.3.4. Central dome

While we find that the emplacement of the Vinalia Faculae occurred after the inflation of the hummocky lobate material (see Sections 3.3.2 and 3.3.3), and that the emplacement of the majority of Cerealia Facula likely occurred after the emplacement of the outer edge of Cerealia Facula (see Sections 3.2.5 and 3.3.1), there are no clearly defined stratigraphic relations between Cerealia Facula and Vinalia Faculae (e.g. Scully et al., 2018b). However, we can tell that the central dome was one of the last features to form within Occator crater, because the radiating fractures on top of the central dome cross-cut the Cerealia Facula bright material (Buczkowski et al., 2018a; Schenk et al., 2018) (Fig. 3i). These fractures, and their vicinity, have different color properties than the Cerealia Facula material, possibly due to an increased dark material component (Nathues et al., 2017; Nathues et al., 2018). Other central pit craters on Ceres do not contain central domes, leading Schenk et al. (2018) to suggest that these are fragile and easily degraded structures. Alternatively, it is possible that a unique property of the Occator region resulted in Occator crater being the only location in which a central dome formed.

Schenk et al. (2018) suggest that the central dome was uplifted via laccolithic intrusion and/or volume expansion from freezing of a central reservoir of volatiles long after the Occator-forming impact. They further propose that the lack of a termination scarp at the edge of the central dome indicates that it was inflated from below rather than being an extrusive feature. However, depending on the viscosity of the extruded material and the emplacement mechanism (e.g. frozen icy carapace above mobile flows), termination scarps may not be formed (S. Fagents personal communication to L. Quick; also see Fagents et al. (2003)). Ruesch et al. (2018a) propose an extrusive formation mechanism for the central dome. In this mechanism, cooling during ascent and carapace formation increased the viscosity of the brines, which extruded onto the surface to build up the central dome. If the central dome was emplaced via the extrusion of briny cryolavas, similar to Ahuna Mons (Ruesch et al., 2016) and putative cryolava domes on the icy satellites (e.g. Quick et al., 2017), the formation time would be ~2.5 days to 9 months, for cryolava viscosities of $10^6$–$10^8$ $m^2/s$, respectively (Quick et al., 2018).

### 3.4. Stage 3 of Occator and faculae formation

#### 3.4.1. Modification of faculae material

The bright Cerealia Facula material has likely become slightly darker over time: small impact craters that superpose the central continuous bright material are surrounded by ejecta blankets of even brighter material, indicating that the Cerealia Facula material at depth is somewhat brighter (Scully et al., 2018b) (Fig. 3j). Bu et al. (2018) find that dehydration of sodium carbonate alone cannot account for the darkening of faculae over time, and propose that mixing with Ceres' average materials and/or space weathering are more likely darkening mechanisms. A photometric analysis indicates that the carbonates in the faculae result in a lack of phase-reddening behavior (Longobardo et al., 2018a).

Palomba et al. (2018) propose an evolutionary pathway for bright regions on Ceres. Bright regions of the Cerealia- and Vinalia-Faculae-type are rich in Na-carbonates and Al-phyllosilicates, and are proposed to be the freshest endmember. The volatilization of OH and small amounts of mixing with average Cerean materials produce Oxo-type bright regions, which are depleted in phyllosilicates and have a high-to-moderate albedo. Continued mixing with average Cerean materials produces Haulani/Ernutet/Kupalo-type bright regions, which are moderately rich in carbonates and slightly depleted in Mg-phyllosilicates and ammoniated phyllosilicates. Finally, the most extensive mixing results in the formation of the common-type bright regions, which have a relatively low reflectance, are composed of Mg-phyllosilicates and ammoniated clays and do not contain high abundances of Mg- and Ca-carbonates.

Both Palomba et al. (2018) and Stein et al. (2018) find that the majority of bright regions on Ceres are found in the rims, walls, floors and ejecta of impact craters. Stein et al. (2018) categorize bright regions based on their location: (1) in crater floors (including crater pits, peaks or floor fractures), such as Cerealia and Vinalia Faculae, (2) in crater rims or walls, (3) in ejecta blankets, and (4) on Ahuna Mons. They conclude that floor faculae are likely formed by impact-induced heating and upwelling of subsurface volatiles and/or by upwelling of extant brines through impact-induced fractures. However, the bright regions in crater rims, walls or ejecta blankets are proposed to form after subsurface bright regions, perhaps previously emplaced on the surface and buried, were excavated by impacts. Stein et al. (2018) also find that faculae darken over time, likely due to combined effects of space weathering and impact-induced lateral mixing, and become unidentifiable on timescales of < 1.25 Gyr.

## 4. Implications

While Occator is the most sodium-carbonate rich location on Ceres (De Sanctis et al., 2016; Raponi et al., 2018), sodium carbonate has been found in lower concentrations in multiple locations across the surface (Carrozzo et al., 2018), indicating that the faculae are not composed of materials that only occur in the Occator region. For example, Ahuna Mons contains one of the highest abundances of sodium carbonate on Ceres, after Occator crater (Zambon et al., 2017; Carrozzo et al., 2018). While they have a similar composition, there are important differences between Occator and Ahuna Mons. For example, the gravity anomaly associated with the Occator region is the most strongly negative gravity anomaly on Ceres, while the gravity anomaly associated with the vicinity of Ahuna Mons is strongly positive (Ermakov et al., 2017). A possible explanation for these observations is that: (i) there is an impact-induced reservoir underneath Occator that is dominated by water and sodium carbonate, which is comparatively less dense than the surrounding crust, and (ii) the reservoir underneath Ahuna Mons is a deeper relict ocean pocket with a greater concentration of salts such as sodium chlorides, potassium chlorides and ammonia (Castillo-Rogez et al., 2018), which are comparatively denser than the surrounding crust (Ruesch et al., 2018b).

By synthesizing together the studies presented in this special issue, we find that the driving forces behind the formation of Occator crater and the faculae are either: (1) entirely exogenic in origin, triggered by the impact or (2) a combination of endogenic and impact-derived forces. We summarize the evidence for these two possibilities in Table 1. Whether activity is impact-triggered and/or endogenic in nature is a key question not only for investigations of Occator and the faculae, but for all investigations of Ceres. As future investigations build upon the studies presented in this special issue, one explanation may become favored.

The research presented in this special issue shows that faculae can be mixed with Ceres' average surface materials on relatively rapid geologic timescales (see Section 3.4.1). Thus, it is likely that similar faculae-forming processes have been ongoing throughout Ceres' history, but only Cerealia and Vinalia Faculae are visible today because they are geologically young. There are other asteroids with surface spectra similar to Ceres, in particular Hygiea (Rivkin et al., 2014 and references therein). If these asteroids underwent a similar evolution to Ceres, geologically young craters on their surfaces may also contain Occator-like faculae, which have yet to be discovered by future exploration. While there are still outstanding questions that remain to be resolved by future investigations, our research to date about Occator, Cerealia Facula and Vinalia Faculae indicates that Ceres is an active world where brines have been mobile in the geologically recent past.

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