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THE FORMATION AND EVOLUTION OF CERES' OCCATOR CRATER.

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Introduction: Ceres is the largest object in the asteroid belt (radius of ~470 km) and was first explored from orbit by the Dawn mission in 2015 [1]. Occator is a ~92 km diameter crater and is one of Ceres' most intriguing and recognizable features thanks to its bright regions [2], called faculae, which are distributed across its floor. Cerealia Facula is in the center and the Vinalia Faculae are in the eastern floor. A ~9 km wide and ~800 m deep central pit contains both a ~300-700 m high central dome and the majority of Cerealia Facula [3-4]. The faculae are mostly composed of sodium carbonate [5].

A variety of studies were undertaken to investigate the driving forces behind the formation of Occator and its faculae [6-19], which will be presented in an upcoming special issue of '*Icarus*' [20-21]. Here we summarize and synthesize together these studies, which give us insights into the processes and conditions that occurred in Ceres' past. Additionally, because of the relative youth of the faculae, this new understanding may also yield insights into Ceres' present-day state.

Synthesis: overview: Based on the aforementioned studies [6-19], we propose the following sequence of events led to the formation of Occator and its faculae. The events are divided into stages 1-3. The stages are sequential, but the events discussed within a stage are not necessarily sequential, unless specifically noted.

Stage 1 of Occator and faculae formation:

Ejecta. The distribution indicates the impactor originated to the NW and impacted at ~30-45° [6]. The NE ejecta blanket has distinct albedo and color properties [e.g. 7]. It is proposed to contain a type of dark material that has a particularly low albedo and has a smaller grain size than the surroundings [11]. This material may only be located to Occator's east, or may be more deeply buried in the west [6,7,11].

Terraces and hummocky crater floor material. During/immediately following crater formation, terraces and hummocky crater floor material were formed by crater-wall collapse and mass wasting [6]. Similar features are found in nearby complex craters [6]. Small fractures circumferential to the interior crater rim also form during transient crater collapse [9].

Lobate material. The lobate materials are morphologically analogous to impact melt [6,17]. Moreover, impact heating is predicted to melt pre-existing water ice, which then formed a solution with the pre-existing salts [13,22]. Thus, 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 [6,13]. This interpretation is consistent with one set of model ages, which indicate the ejecta and lobate materials formed essentially contemporaneously [10]. The lobate materials are alternatively proposed to be a debris avalanche deposit [7 and references therein].

Central pit. Occator's central pit is the least degraded of ~11 examples identified on Ceres [17]. A set of concentric fractures likely formed as the pit collapsed [9,17]. Some of these fractures cross-cut the lobate materials, indicating that at least portions of the lobate materials solidified prior to central pit formation [6,9,17]. The 'melted uplift model' is suggested to form Occator's central pit, via drainage of an initial liquid-water central uplift into impact-induced fractures [see 17 and references therein].

Outer edge of Cerealia Facula. This is a discontinuous ring of bright material that is mostly outside of the central pit. It is cross-cut by fractures concentric to the central pit, indicating it formed early in Occator's history [6,9,17]. Hydrothermal circulation and brine deposition are predicted to occur shortly following the crater-forming impact [13,22]. Thus, residual salts left after vaporization of the impact-derived brines are proposed to form the outer edge of Cerealia Facula.

Stage 2 of Occator and faculae formation:

Majority of Cerealia Facula (besides outer edge). The majority of Cerealia Facula is located within the central pit and is a roughly circular deposit of bright material that has a continuous appearance [e.g. 6,8,17]. The faculae contain sodium carbonate, ammonium chloride and Al-phyllosilicates [11], which is consistent with Na_2CO_3 forming regardless of brine freezing rate [16]. Photometry indicates the faculae have a greater roughness and/or lower abundance of opaque material than the surroundings [12]. Mineralogical variations across Cerealia Facula indicate the occurrence of different depositional events [11]. Brines are proposed to flow out of fractures in the walls of the central pit, forming bright tendrils on the walls, before collecting to form the majority of Cerealia Facula in the central pit [17].

Model ages suggest the majority of Cerealia Facula formed long after Occator, perhaps at least ~18 Myr [7,10]. However, current models suggest that impact-induced brine deposition would only last for ~1-5 Myr after the impact [13]. Thus, the long-lived emplacement of Cerealia Facula may require a pre-existing brine reservoir. Volume changes induced by a freezing reservoir could drive brines to the surface, forming the faculae [14]. Salt-rich water fountains could emplace the brines on the surface [8]. However, the predicted composition of a pre-existing reservoir (sodium and potassium chlorides, and ammonia) [23-24] may be inconsistent with the observed faculae composition (dominantly sodium carbonate and ammonium chloride) [5,11]. Future studies and refinements of the current results may resolve these inconsistencies.

Floor fractures and hummocky lobate material. Piston-like uplift of the crater floor by a cryomagmatic intrusion is proposed to form long concentric fractures around the base of Occator's wall [9]. Cryomagmas likely used the fractures to upwell under the surface, forming an asymmetric dome in the SW floor [9]. Another injection of pre-existing reservoir material is proposed to result in the inflation of part of the lobate materials, giving them their hummocky texture [9].

Vinalia Faculae. The uplift of the hummocky lobate material is proposed to form fractures [9], which the brines used to ascend to the surface [6-9,14,17] before salt-rich water fountaining deposited them on the surface [8]. Less than 1 wt% volatiles can drive ballistic eruptions to form the Vinalia Faculae [14]. One possible explanation for the lower concentration of compositional components in Vinalia Faculae than in Cerealia Facula is that Vinalia Faculae formed over a less prolonged timespan [11].

Central dome. The radiating fractures on top of the dome cross-cut the bright Cerealia Facula, indicating the central dome was one of the last features to form [9,17]. Freezing of ice, a subsurface intrusion, extrusion of higher viscosity brines or extrusion of briny cryolavas are all possible formation mechanisms of the central dome [8,14,17]. There are no other central domes on Ceres, suggesting they are easily destroyed or that a unique property of the Occator region facilitated the formation of the dome [17].

Stage 3 of Occator and faculae formation:

Modification of faculae material. Small impacts into the faculae expose brighter materials, indicating that their surface has been somewhat darkened over time [6], most likely by mixing with Ceres' average materials and/or space weathering [15]. An evolutionary path is proposed for bright regions on Ceres, and Occator's faculae are the first step on this evolutionary pathway [19]. The majority of the bright regions on Ceres are found to form after previously emplaced surficial bright regions were buried and then re-excavated by impacts, and bright regions are found to darken and become unidentifiable in <1.25 Gyr [18]. It is likely that faculae-forming processes have been ongoing throughout Ceres' history, but only Occator's faculae are visible today because they are geologically young.

Implications: We find that the driving forces behind the formation of Occator crater and the faculae are either: (1) an exogenic/impact driving force or (2) a combination of endogenic and exogenic driving forces. Future studies and refinements of the current results are needed before one explanation can be favored.

Sodium carbonate is not only found in Occator [25]. Ahuna Mons also contains a high concentration of sodium carbonate [25-26], but the Ahuna-Mons region has an opposite gravity anomaly to Occator [27] and Ahuna Mons does not appear to be directly related to impact processes [28]. Thus, there are open questions about how the formation of Occator's faculae and Ahuna Mons can be tied to their compositions and gravity anomalies, some of which may be resolved during Dawn's second extended mission at Ceres.

While there are open questions to be resolved by future investigations, our research to date about Occator and its faculae indicates that Ceres is an active world where briny liquids have been mobile in the geologically recent past.

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