Formation and Evolution of Occator Crater and Its Faculae on Dwarf Planet 1 Ceres.

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Introduction: The 92 km diameter crater Occator in Ceres’ northern hemisphere is perhaps the most enigmatic feature on the dwarf planet, and hosts the highest albedo features on the body [1]. These bright spots (named faculae) within Occator are dominantly composed of sodium rich carbonates [2], and exist largely within two regions of the crater. Cerealia facula is a dome of bright carbonate deposits that dominate the center of Occator [1-2]. This dome sits within a central pit similar in morphology and scale to those seen within craters on icy satellites [3]. Venalia faculae are a set of bright deposits within the northeast quadrant of Occator [1]. While spread out over a greater area and less voluminous, they have a similar composition and albedo as Cerealia facula [2].

The mechanism behind the formation of Ceres’ faculae, and their genetic relationship to the impact that formed Occator, is currently debated. When Occator formed, a significant amount of heat was deposited within the subsurface [4]. Because Ceres likely contains a significant fraction of water ice [5-6], this hot material would be capable of driving a temporary hydrothermal system, particularly in the center of the crater where the hottest material would have been concentrated [4]. Hydrothermal brines, upon interaction with the surface, could have sublimated, forming ballistically emplaced deposits of salts and carbonates within the center of the crater [7-8]. Alternatively, fractures induced by the Occator forming impact could have allowed for the transit to the surface of cryo-lavas from a pre-existing subsurface fluid reservoir unrelated to impact heat, both erupting onto the surface as well as forming an uplifted dome [9].

Although Occator a young, fresh crater [10-11], its morphology and composition still have important implications for ancient bombardment on the body. The presence of faculae within Occator strongly suggests that the crater’s morphology was modified post-impact by hydrothermal and/or cryovolcanic processes. These processes should have effected all craters on Ceres, and must be accounted for in order to understand the effects of the dwarf planet’s early bombardment history.

Detailed models of both Occator’s formation and evolution are required in order to understand the unique structure of the crater and what it implies about the anatomy and history of Ceres’s interior. In order to address this holistically, we directly couple models of Occator’s formation, a process dominated by impact shock and high strain rate flow, to hydrothermal simulations, which reproduce the long term evolution of fluid flow beneath the hot, fresh crater.

Methodology: We simulate the formation of Occator crater using the shock hydrodynamics code iSALE [12-14]. Our crater is formed when a main-belt like impactor traveling at typical Cerean impact velocities collides with a surface composed of a mixture of H2O ice and serpentine [4]. We implement a simple model that described how permeability within the subsurface develops as a function of porosity [15]. The results of our iSALE simulations describe the distribution of temperature, porosity, permeability, and water content at the center of the crater formation process and at the onset of hydrothermal circulation. The output from these simulations is then directly mapped into the hydrothermal evolution code HYDROTHERM, which describes water and heat transport in porous geologic media [16]. HYDROTHERM, which was developed to account for terrestrial hydrothermal systems, has been modified to account for the enthalpy of freezing, making it capable of modeling low temperature conditions such as those found at the surface of Ceres. In combination, these simulations allow for a detailed examination of both the formation and evolution of hydrothermal systems within the Cerean subsurface.

Results: The impact that formed Occator heated significant volumes of material above the eutectic of subsurface brines [7], allowing for effective fluid circulation immediately after crater formation. The total volume of hydrothermally viable material is dependent on the water-serpentine ratio of the pre-impact surface, with higher water contents resulting in larger volumes of hot fluids. Hydrothermal circulation within the subsurface of the crater is largely constrained to a hot ‘plug’ in the center of the crater. Inward flow of fluids from depth leads to large amounts of effusion at the center of the crater. The hottest regions of the subsurface are largely composed of impactor material, which drives localized, relatively rapid fluid circulation. The lifetime of the system varies considerably depending on permeability, but has a maximum duration of a few hundred thousand years. Pressure, temperature, and water/rock ratio time-series for parcels of fluid within our simulations can be used to inform models of the chemical evolution of the brines that formed the faculae observed on Ceres.
**Formation of Faculae and Occator’s Central Pit:** Recent observations by the Dawn spacecraft’s 2nd extended mission can provide new insights into the crater’s formation, evolution, and the origin of Ceres’ faculae. Very high resolution images of Cerealia facula (Figure 1, [17]) seem to show that the bright carbonate deposits within the crater lie both on the rim of as well as in a dome at the bottom of the crater’s central pit. This may imply that the central pit of the crater formed either contemporaneously with or after the deposition of the faculae.

Central pits within craters on icy satellites and Mars are thought to form when H$_2$O impact melt, which is concentrated in a plug within the center of the crater, drains downward through impact induced fractures into the subsurface [18]. However, the presence of faculae deposits and our simulations of hydrothermal circulation imply that impact induced heating drove hydrothermal effusion of brines upwards onto the surface. Our results suggest that subsidence driven by the loss of material via hydrothermally driven brine effusion and sublimation lead to the collapse of Occator’s central pit. This brine effusion also can explain the formation of the faculae as evaporite deposits left behind after sublimation of the H$_2$O component of the brines. Under this model, Cerealia facula initially began to form before the collapse of the central pit, producing the portions of the bright deposits that currently exist on the pit rim. As the pit began to subside, much of the bright deposited material was subsumed downwards. Continued effusion of brines lead to the deposition and uplift of a central dome within the pit.

Our iSALE models imply that the hottest regions within the post-impact surface are composed of impactor material, consistent with previous models of impact heating [19]. Because our simulations are two dimensional and axisymmetric, most of this impactor material is concentrated within the center of our final crater’s subsurface. However, during oblique impacts, a significant portion of the impactor can travel into the subsurface in the downrange direction, potentially outside of the region of hydrothermally viable material which in our simulations is largely constrained to the crater center. Although not explicitly modeled, this off-axis hot material could potentially drive a secondary hydrothermal system with a shorter lifetime than the hydrothermal system within the center of the crater. Such a system could potentially form a secondary deposit of bright material on the crater floor such as Vinalia faculae. If this is the case, the location of Vinalia faculae implies that Occator was formed during an oblique collision with a projectile impinging on the Cerean surface from the west or southwest.


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![Figure 1](https://example.com/ocator.png)

**Figure 1:** View of Occator crater with inset from Dawn’s 2nd extended mission showing bright material on the rim of the central pit [17].