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Science Drivers for the Future Exploration of Ceres: From Solar System Evolution to Ocean World Science

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Abstract

Dawn revealed that Ceres is a compelling target whose exploration pertains to many science themes. Ceres is a large ice- and organic-rich body, potentially representative of the population of objects that brought water and organics to the inner solar system, as well as a brine-rich body whose study can contribute to ocean world science. The Dawn observations have led to a renewed focus on planetary brine physics and chemistry based on the detection of many landforms built from brines or suspected to be emplaced via brine effusion. Ceres' relative proximity to Earth and direct access to its surface of evaporites that evolved from a deep brine reservoir make this dwarf planet an appealing target for follow-up exploration. Future exploration, as described here, would address science questions pertinent to the evolution of ocean worlds and the origin of volatiles and organics in the inner solar system.

Unified Astronomy Thesaurus concepts: [Ceres \(219\)](#); [Dwarf planets \(419\)](#); [Surface ices \(2117\)](#)

1. Introduction

In the last decade of planetary exploration, the investigation by the Dawn mission of the dwarf planet Ceres, the most water-rich body in the inner solar system after Earth and largest object in the main asteroid belt, proved to be a major milestone. Ceres had sufficient H₂O and silicates (i.e., radioisotopes) to host subsurface liquid water throughout its history, leading to a layered interior structure with a high degree of aqueous alteration (Ermakov et al. 2017; Fu et al. 2017; Park et al. 2020). Deposits of bright carbonates and phyllosilicates are indicative of pervasive and global aqueous alteration (Ammanito et al. 2016; De Sanctis et al. 2016; Carrozzo et al. 2018). The Dawn mission also revealed evidence for recent and even ongoing geological activity on Ceres (Ruesch et al. 2016; De Sanctis et al. 2020), the presence of liquid—at least locally—below an ice-rich crust (Ruesch et al. 2019a; Scully et al. 2020), high concentrations of organic matter (OM; locally) and carbon (globally) in the shallow subsurface (De Sanctis et al. 2017; Prettyman et al. 2017; Marchi et al. 2019), and the

presence of an exosphere and volatile transport (Villarreal et al. 2017; Formisano et al. 2018). Even though the extent of a liquid layer in Ceres at present is not well understood, Ceres displays evidence for the past and recent occurrence of a variety of processes that are relevant to ocean worlds.

This paper reviews the state of knowledge of Ceres after Dawn, including emerging interpretations about its evolution and the state of its residual liquid brine (Section 2). Then, we review how knowledge of Ceres contributes to better understanding the evolution of other large water-rich bodies, and we describe the relevance of Ceres' study to other science themes (Section 3). Based on these considerations, we offer recommendations for the future research and exploration of Ceres with the purpose to further contribute to the fields of planetary origins and ocean world science (Section 4).

2. Key Dawn Results at Ceres

Pre-Dawn, Ceres was known to be a volatile-rich body that accreted ice and carbonaceous material early in the history of solar system formation (O'Brien & Sykes 2011). Given the high temperatures on Ceres' surface compared to the icy satellites of the outer solar system, water ice sublimates when exposed at the surface and could only be detected in a few locations by Dawn. The largest area of water ice is located in



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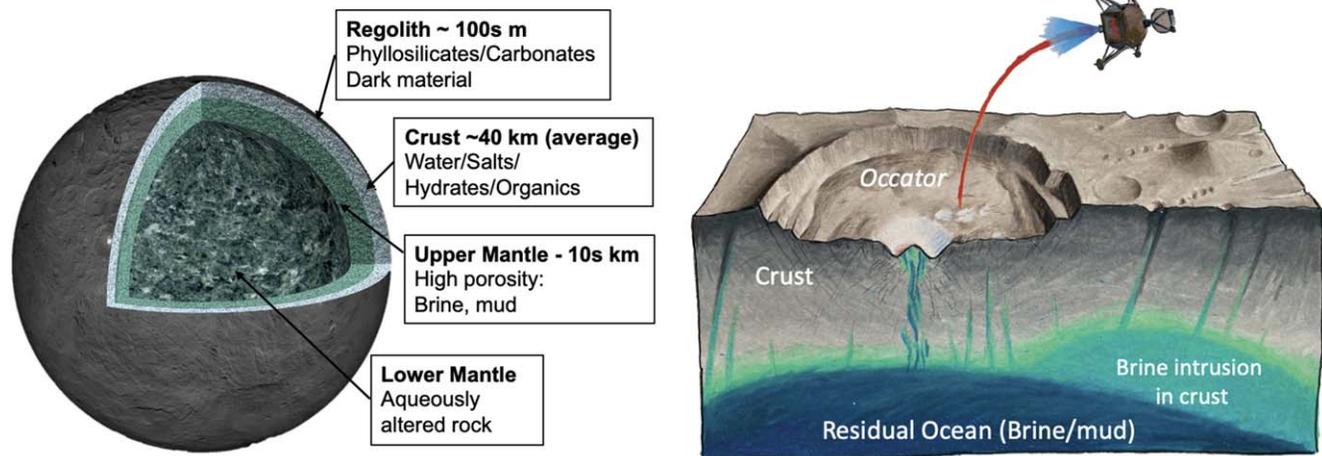


Figure 1. Left: current understanding of the global interior structure for Ceres after Ermakov et al. (2017) and Fu et al. (2017); a strong crust overlays a low-density rocky mantle. Evidence for recently exposed salts at Occator crater and Ahuna Mons suggests the presence of deep brines at the interface between the crust and mantle, at least locally, which are the likely remnants of a thicker subsurface ocean present in Ceres' early history. Right: possible structure of the crust and upper mantle inferred below the 90 km diameter Occator Crater (~50 km thick crust; Ermakov et al. 2017). The impact crater created a transient melt chamber and also introduced or reactivated fractures allowing for the long-term upwelling of deep brines (Raymond et al. 2020). Left panel: reprinted from Castillo-Rogez et al. (2020). Right panel: credit: J. T. Keane.

Oxo crater (Combe et al. 2016), and there are smaller patches in the northern hemisphere (Combe et al. 2019), including where persistently shadowed regions are present (Platz et al. 2016). However, the Dawn mission revealed several lines of compelling evidence for an ice-rich crust.

1. Gravity inversions yield a low crustal density of $\sim 1300 \text{ kg m}^{-3}$ (Ermakov et al. 2017), consistent with a crust dominated by low-density materials and less than 20 wt.% rock.
2. Crater morphometry nearly exactly matches that of icy satellites (Hiesinger et al. 2016). Consideration of crater relaxation is consistent with the shallow subsurface being up to 40% ice by volume, though this ice content may vary laterally and with depth (Bland et al. 2016; Otto et al. 2019; Sizemore et al. 2019).
3. Distinct morphologic features can be attributed to a large fraction of ice in Ceres' crust. These features include known volatile-related morphologies, such as fractures related to intrusion (uplift), pitted terrains, and flow-like mass-wasting features (Schmidt et al. 2017; Scully et al. 2017; Sizemore et al. 2019). Furthermore, the occurrence of small ring-mold craters and 100 m scale hills with pingo-like morphologies (Schmidt et al. 2020) within Occator crater suggests localized water-ice reservoirs in the shallow and lower subsurface (Krohn et al. 2018).
4. Global, pervasive aqueous alteration of surface material (Ammannito et al. 2016) and abundant morphologic evidence, such as pervasive fracturing or mounds, hint at the existence of deep liquid throughout Ceres' history. Flow features have been found in and around craters. For example, Occator's interior exhibits extended plains of ponded material and extensive lobate materials, which may be representative of water or ice-rich flows (e.g., Krohn et al. 2016; Scully et al. 2018; Schenk et al. 2019). Those features are also found around the craters Haulani, Kupalo, Ikapati (Krohn et al. 2016), Kerwan, Yalode, and Urvara (e.g., Williams et al. 2018; Bland et al. 2019). Multiple flow stages and discrete feeding sources may be consistent with a cryovolcanic origin for these flows

(Krohn et al. 2016), although they are likely expressions of impact-generated melt in an icy crust (Schenk et al. 2020).

5. Salt compounds, in particular sodium carbonate, have been detected locally in high concentrations (Carozzo et al. 2018); thermodynamic models suggest that in addition to water, other volatile compounds were accreted by Ceres, in particular ammonia and carbon dioxide (De Sanctis et al. 2015; Castillo-Rogez et al. 2018).
6. The potential presence of an exosphere is suggested by ground-based observations (see Rousselot et al. 2019 for a review) and a possible haze signature at Occator crater (Nathues et al. 2019).

In addition to ice, there is evidence for abundant organic material in the shallow subsurface. The regolith contains a large fraction of carbon, greater than 10 wt.% on a global scale (Prettyman et al. 2017; Marchi et al. 2019), and organics with aliphatic functions, at least $>10 \text{ vol.}\%$ locally (De Sanctis et al. 2017). On the other hand, Zolotov (2020) suggested a different interpretation for the density profile inferred by Ermakov et al. (2017) that assumes a high fraction of OM and little or no ice. This model can explain the high content of carbon found in the regolith, but its viability for explaining Ceres' geology needs to be demonstrated.

In this section, we address salient open questions about Ceres' interior, in particular evidence for the presence of a residual ocean or regional brine reservoirs and the nature of that environment.

2.1. Evidence for Brines in Ceres at Present and Recent Activity

Geophysical and geological observations hint at the existence of a former subsurface ocean whose remnants are still shaping the geology of the surface today (Ruesch et al. 2019a, 2019b). Based on admittance values derived from Dawn topography and gravity data sets, a rocky mantle starts about 40 km below the surface, on average (between 35 and 55 km; Ermakov et al. 2017; Fu et al. 2017; Figure 1). The nature of

this interface, a transition to solid rock or muddy ocean, is debated. The mantle density inferred by Ermakov et al. (2017) of 2430 kg m^{-3} may be significantly lower than the grain density predicted by chemical modeling (Castillo-Rogez et al. 2018), suggesting possible high porosity. However, a mantle density of up to $\sim 2800 \text{ kg m}^{-3}$ may be possible if Ceres was despun and retained a fossil shape (Mao & McKinnon 2018), in which case, the bulk porosity may be $<10 \text{ vol.}\%$. An additional global constraint on the presence of a deep liquid layer comes from the topography relaxation models performed by Fu et al. (2017). These authors found that an $\sim 40\text{--}45 \text{ km}$ high-strength crust above a low-viscosity layer, i.e., at the top of the mantle, best reproduces Ceres' topography. However, the viscosity of the upper mantle is poorly constrained at $<10^{21} \text{ Pa s}$ (Fu et al. 2017). Below, we focus on two features, Occator crater and Ahuna Mons, whose association with deep brines are supported by multiple observations, in particular geophysical data (gravity) and compositional data (salts). Their young emplacement age suggests that the brine reservoir still exists. Outside of these regions, geophysical evidence for deep liquid is lacking.

Occator crater is a relatively young ($\sim 20 \text{ Myr}$; Neesemann et al. 2019), large crater with bright materials, including sodium carbonates and salt-rich materials, that represent evaporites from recent resurfacing ($<2 \text{ Myr}$; Nathues et al. 2020). The morphology of Cerealia Tholus, a $\sim 600 \text{ m}$ high mound at the center of Cerealia Facula, is reminiscent of putative cryolava domes on Jupiter's moon Europa (Fagents 2003; Quick et al. 2017). Emplacement mechanisms for the sodium carbonates and salt-rich bright materials in Occator (called faculae) include brine-driven cryovolcanism from a deep reservoir beneath the crust (e.g., De Sanctis et al. 2016; Krohn et al. 2016; Nathues et al. 2017; Quick et al. 2019; Ruesch et al. 2019a) and a shallower melt chamber produced by impact-generated heat (Bowling et al. 2019; Raymond et al. 2020; Schmidt et al. 2020; Scully et al. 2020). The latter was estimated to be at least 6 km in diameter and 20 km deep (Bowling et al. 2019). The lifetime for that chamber was estimated by thermal modeling to be 10 Myr at most (Hesse & Castillo-Rogez 2019) and likely much less when convective heat transfer is accounted for. Hence, long-lived activity in Occator likely involved the contribution of a perennial deep brine reservoir whose connection with the surface was enabled by fractures created by the impact (Quick et al. 2019; Raymond et al. 2020). The dual origin for the brine can also explain the difference in evaporite deposit morphologies; at the center of the crater, Cerealia Facula is thick and continuous, whereas the Vinalia Faculae, distributed along the fractures on the eastern side of the crater floor, are thin, discontinuous, and somewhat diffuse (Ruesch et al. 2019b; Scully et al. 2020). Additionally, the existence of hydrated sodium chloride, a salt that dehydrates on a timescale of only centuries, in Occator crater suggests the presence of subsurface liquid brines today (De Sanctis et al. 2020). Besides Occator, a dozen craters display floor fractures that have been explained by shallow, cryomagmatic intrusions (Buczowski et al. 2018; Krohn et al. 2020). These intrusions may also indicate sourcing from underlying reservoirs, forming domes that uplift and fracture the overlying, brittle crater floor (Buczowski et al. 2018; Krohn et al. 2020). However, these craters are more ancient than the $\sim 20 \text{ Myr}$ old Occator crater.

The $\sim 4 \text{ km}$ tall Ahuna Mons is a young mountain with steep flanks proposed to be a cryovolcanic construct formed in the past tens or hundreds of megayears (Ruesch et al. 2016). Bright

streaks on its flanks contain sodium carbonates (Zambon et al. 2017). The emplacement of such a large mons requires a low-viscosity material (Ruesch et al. 2016). Geophysical observations indicate that the mons material is dense and was sourced from the top of the mantle (Ruesch et al. 2019a). These combined observations indicate an origin involving a mud- or brine-rich material. Other mountains and domes (Buczowski et al. 2016) have also been argued to be older, degraded cryovolcanic constructs on the basis of geophysical and geomorphological arguments (Sori et al. 2017, 2018), although some of them may also have been formed by intrusive processes instead (Bland et al. 2019).

2.2. Assessing Ceres' Past and Current Habitability Potential

In addition to the above evidence for subsurface liquid water, the surface of Ceres is blanketed with products deriving from the interaction of rock and liquid water, which can supply chemical energy and bioessential elements in inorganic or organic form and are the basic requirements of a habitable environment. While most of Ceres' compositionally homogeneous dark surface was likely emplaced early in solar system history, select areas of the surface appear geologically very recent and compositionally distinct, and they provide information about the habitability of environments on Ceres both in the geologic past and at recent (perhaps present) times.

Bioessential elements. Local concentrations of organic carbon have been detected on the surface as prominent $3.4 \mu\text{m}$ spectral absorption features, and an inorganic carbon source is also available from carbonates. Combined data from the Dawn visible and infrared mapping spectrometer (VIR) and the gamma-ray and neutron detector also indicates that the global regolith contains $10\text{--}20 \text{ wt.}\%$ of amorphous carbon (Marchi et al. 2019). From laboratory mixtures, a similar amount is proposed (as a mixture of aliphatic and aromatic carbon) to fit the spectral abundance of the local OM observed at Ernutet crater (Vinogradoff et al. 2021). The large amount of OM and amorphous carbon found in the regolith may be representative of the crustal composition or may have been concentrated by an unknown mechanism. Nitrogen has been detected as a constituent of ammonium salts (Raponi et al. 2019). Sulfur is expected to be in the form of sulfides (e.g., of iron and nickel), but these compounds do not have a signature detectable by VIR. Oxygen and hydrogen are inferred to be present as components of organics, ice, and ammonium-bearing species. Aliphatic-dominated OM has been found in the region of Ernutet crater with at least three to four times greater abundance than in carbonaceous chondrites (Kaplan et al. 2018; De Sanctis et al. 2019; Vinogradoff et al. 2021). The precise composition of this OM could not be derived from the Dawn observations. However, the mixing of the organic signatures found at Ernutet crater with other surface material (phyllosilicates, carbonates) suggests that these organics formed inside Ceres (Vinogradoff et al. 2021), although an exogenic origin cannot be definitely discarded.

Chemical energy. Theoretical energy sources could be provided by organics on their own (fermentation) or as half-reactions with sulfates, for example, in anaerobic respiration. However, these assessments require greater knowledge of the chemistry of the organic material. Other sources of chemical energy are also possible (see Section 3.1).

Habitability potential early in solar system history. The overall homogeneity of Ceres' regolith suggests that it was

emplaced globally during the first 100 million yr after formation, when liquid water was present on a global scale in the subsurface due to short-lived radionuclides as a primary heat source (e.g., Castillo-Rogez & McCord 2010; Neveu & Desch 2015; Travis et al. 2018; Castillo-Rogez et al. 2019). The homogenous dark regolith is mainly composed of an unknown darkening agent (likely carbon and/or Fe compounds; Marchi et al. 2019), Mg-bearing serpentine, ammonium-bearing clays, and Ca- and/or Mg-bearing carbonates (De Sanctis et al. 2015; Ammannito et al. 2016). Modeling suggests that these compounds can together result from the complete reaction between liquid water and chondritic material in the presence of CO₂ and NH₃, which generates alkaline conditions (pH > 7). Specifically, and although this remains to be confirmed experimentally, the presence of NH₄ suggests formation at pH > 10 and temperatures lower than 50°C, yielding ionic strengths on the order of 0.1–1 (Neveu et al. 2017; Castillo-Rogez et al. 2018). It may be that earlier conditions were hotter, and that the incorporation of ammonium into clays occurred at later, colder conditions. Early redox conditions are constrained to hydrogen fugacities between 10⁻⁸ and 10⁻⁵ bars by the coexistence of relatively oxidized carbonates and relatively reduced nitrogen (as ammonium clays), as well as amorphous or organic carbon (Neveu et al. 2017; Castillo-Rogez et al. 2018).

Habitability potential today. The current physicochemical conditions of Ceres' brine reservoirs are not well constrained. Bounds on temperature can be derived from the mineralogy observed in recently exposed evaporites. Occator's bright faculae are composed of sodium carbonate (up to 70 vol.%), ammonium chlorides (up to 7 vol.%), and, in the case of Cerealia Facula, a few percent of hydrohalite (Raponi et al. 2019; De Sanctis et al. 2020). At Ahuna Mons, sodium carbonate has been found at a level of 7–10 vol.% (Zambon et al. 2017). These observations suggest that the source temperature should be at least 245 K (Castillo-Rogez et al. 2019). On modern Ceres, although sodium carbonate is indicative of an alkaline environment (pH ~ 7–10; Castillo-Rogez et al. 2018), and surface expressions of cryovolcanism point to subsurface liquid reservoirs on the verge of complete freezing, more specific constraints are lacking on the conditions (redox, pH, ionic strength, temperature, etc.) in Ceres' deep, cold, concentrated brines and whether that environment is within the limits that psychrophilic and halophilic organisms can tolerate (e.g., Pikuta et al. 2007).

3. Big-picture Significance: Contribution of Ceres Science to Other Fields

As an ice-rich body, a dwarf planet, and the largest member of the main asteroid belt, the exploration of Ceres provides insights into properties and processes that may affect other large water-rich asteroids, dwarf planets, and icy satellites (see Figure 2 for a review of the basic physical properties). In that respect, Ceres is unique in the inner solar system. Ceres shows many similarities to ocean worlds in the outer solar system because of its differentiated interior and brine composition that is partly similar to Enceladus's plume grains (Postberg et al. 2011; De Sanctis et al. 2016). Similar chemistry based on the evolution of carbon dioxide and ammonia in solution (Marion et al. 2012) is relevant to, for example, the Uranian satellites (Cartwright et al. 2020) and likely Pluto (Dalle Ore et al. 2019). Even if Ceres does not host a global subsurface liquid layer at

present, recent and likely ongoing exposure of evaporites in Occator crater make it a compelling place for testing habitability paradigms by determining the environmental properties of Ceres' residual ocean with in situ exploration and/or sample return (J. C. Castillo-Rogez et al. 2022, in press). Furthermore, Ceres is a likely representative of the population of planetesimals that brought organics and water to the inner solar system and might even be an example of the large planetesimals that supplied Earth with the majority of its volatiles (e.g., De Sanctis et al. 2015; Budde 2019). Lastly, in situ/sample return exploration of Ceres in the next decade would be complementary to the ongoing sample return missions from C-type near-Earth asteroids (NASA's OSIRIS-REx, JAXA's Hayabusa-2) and ocean world missions in the outer solar system that will be launched in the mid-2020s (NASA's Europa Clipper and Dragonfly, ESA's Jupiter Icy Moons Explorer).

3.1. Contribution of Ceres Exploration to Ocean World Science

3.1.1. Extent of Internal Evolution in Water-rich Bodies

Insights into the aqueous alteration of planetary materials have been primarily derived from the analyses of carbonaceous chondrites. Among planetary materials investigated in the laboratory, the CM and CI carbonaceous chondrites were likely formed in relatively small (<100 km diameter) planetesimals (Brearley 2006). The degree of alteration of these chondrites is deduced mainly from petrography, petrology (Browning et al. 1996; Rubin et al. 2007), and modal composition (Howard et al. 2015) and, to some extent, from the abundances and isotopic compositions of volatiles (Alexander et al. 2013). A progressive sequence of reactions with increasing temperature first produces Fe-serpentine and tochilinite, which are then converted to Mg-serpentine, magnetite, clay, and sulfates (Howard et al. 2011). The OM is modified, and carbonates are also produced during aqueous alteration (see, for example, Alexander et al. 2015). In CM and CI parent bodies, these reactions occurred at relatively low temperatures (<100°C), and, although they required liquid water, the water/rock ratios were low (<1; e.g., Verdier-Paoletti et al. 2019), and water did not differentiate from rock on a global scale (e.g., Bland & Travis 2017).

The alteration mineralogy determined from Ceres' surface spectra is similar to the most highly altered carbonaceous chondrites, but more extreme (McSween et al. 2018). Ceres is spectrally similar to a few other C-class asteroids that may have also experienced extensive aqueous alteration, such as 10 Hygiea (e.g., Rivkin et al. 2014). These bodies, like Ceres, are among the largest asteroids, suggesting that the degree of alteration (and differentiation) of water-bearing planetesimals is related to size (McSween et al. 2018). Although the primary and alteration mineralogy of even larger ocean worlds is not well constrained, Ceres serves as a bridge linking smaller, altered, but undifferentiated planetesimals to larger bodies with subsurface oceans. Ceres also represents an example of an aqueously altered planetary body for which we have a lot of observations and whose physical properties (e.g., size, water and rock fractions) are similar to or approaching those of ocean worlds in the outer solar system (Figure 2). Ceres' large mass (and thus volume) of water led to a deep ocean in its early history that could have driven pervasive aqueous alteration and long-lived hydrothermal circulation (Travis et al. 2018). Ceres'

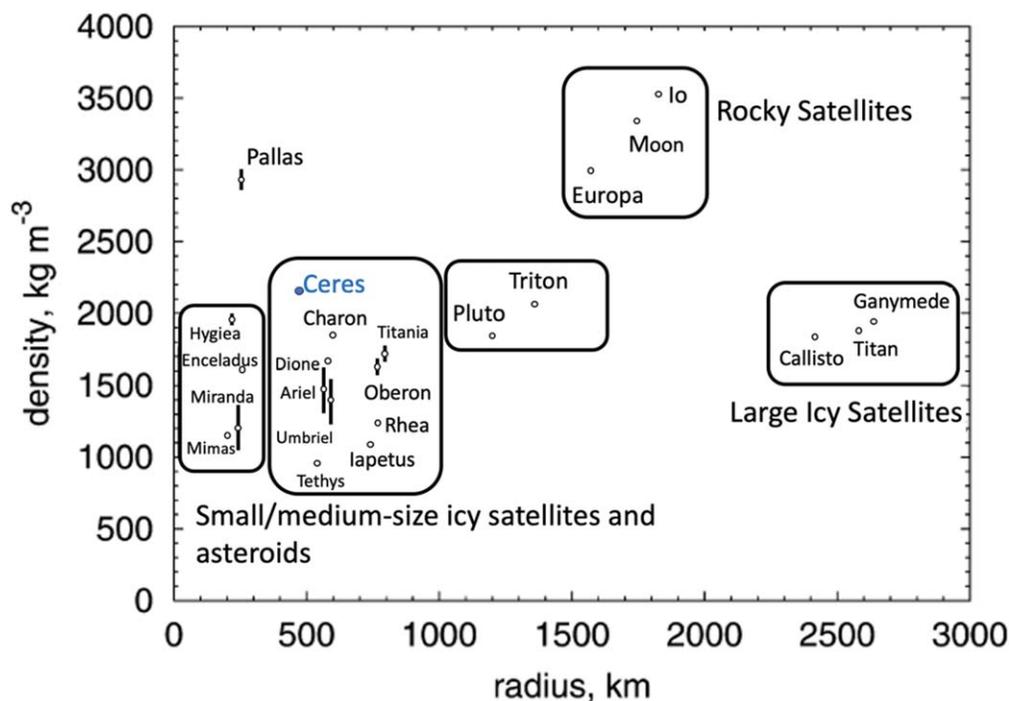


Figure 2. The basic physical properties for ice-rich bodies (and rocky satellites) highlight the similarities between Ceres and mid-sized icy moons (figure based on Hussmann et al. 2006). Hence, knowledge gained at Ceres can inform the physical evolution of mid-sized icy moons, and vice versa.

effective W/R, i.e., the ratio of the mass of water thermodynamically equilibrated with the mass of rock, has been inferred to be >3 based on surface mineralogy (Castillo-Rogez et al. 2018). For comparison, the W/R in Enceladus's fractured rocky mantle has been inferred to be ~ 4 (Sekine et al. 2015). However, it is possible that only a fraction of Ceres' rock was involved in aqueous alteration processes. If large particles (a few millimeters across; e.g., calcium aluminum inclusions and chondrules) gravitationally settled into Ceres' interior rapidly during the differentiation phase (Neveu & Desch 2015; Castillo-Rogez & Bland 2021), then aqueous alteration of these particles and their contribution to the early ocean composition may be limited. On the other hand, organic and more volatile-rich material, which tends to be associated with the fine-grained matrix in chondrites, would be physically fractionated as a result of longer settling timescales relative to the larger particles or would stay in suspension for a long time (e.g., Bland & Travis 2017). Since these volatile and organic materials are of key interest for habitability and geologic activity in ocean worlds, a better accounting of their fate during differentiation is the basis of understanding geochemical cycles, with implications for predicting and interpreting, e.g., plume composition, origins of atmospheres, volatile inventories, bioavailable energy, and nutrients. Moreover, the fractionation of accreted material in a large ocean is likely relevant to a wide range of bodies. For example, Scott et al. (2002) pointed out that dense, iron-rich particles may settle on a faster timescale than less dense particles, potentially leading to the low-temperature differentiation of a metallic core in Ganymede. A similar process may explain the depletion of iron in Ceres' regolith relative to carbonaceous chondrite compositions (Prettyman et al. 2017). On a different note, recent studies emphasize the potentially high concentration of OM in the mantles of Titan (Neri et al. 2020) and Pluto (McKinnon et al. 2021). However, these studies did not explore the potential

degradation of OM during the differentiation phase (see Scott et al. 2002). This is important in understanding, for example, how the thermal evolution of the organics trapped in the rocky mantle could release and replenish hydrocarbons in Titan's atmosphere (Miller et al. 2019).

Ceres' relatively low gravity implies that its rocky mantle could contain a significant fraction of porosity following differentiation. A similar structure has been suggested for Saturn's mid-sized moons (Roberts 2015; Travis & Schubert 2015; Choblet et al. 2017; Neveu & Rhoden 2019). In the case of Enceladus, Iess et al. (2014) inferred a mantle density of $\sim 2400 \text{ kg m}^{-3}$, similar to the Ermakov et al. (2017) estimate for Ceres' mantle. That value corresponds to about 30% brine-filled porosity in bulk, assuming a brine density of $\sim 1200 \text{ kg m}^{-3}$ (Quick et al. 2019) and a rock density of at least 3000 kg m^{-3} as predicted by geochemical models (Castillo-Rogez et al. 2018). In practice, sorting of rock particles during differentiation (Neveu & Desch 2015; Bland & Travis 2017) could lead to a low-porosity rocky core overlain by a mixture of brines, fines, and OM. A similar structure could apply to mid-sized moons if they accreted from chondritic or cometary material (i.e., a mixture of fines, large particles such as chondrules, and OM). Confirming the presence and nature of brine-filled porosity inside Ceres should be a prioritized objective of a future mission, as this kind of medium could host favorable conditions for prebiotic chemistry (e.g., Nisbet et al. 2007).

A key question is the extent of thermal evolution of the mantle and whether it reached metamorphic conditions leading to partial dehydration. Ceres' mantle density is uncertain, between 2400 and 2800 kg m^{-3} (Ermakov et al. 2017; Mao & McKinnon 2018). A dehydrated mantle composed of olivine and pyroxene would produce a bulk density higher than that inferred for Ceres; thus, it is possible that the mantle did not dehydrate, and some fluid must have been retained to allow

retrograde formation of some hydrous phases, or the mantle has retained some porosity filled in by brines (e.g., Melwani Daswani & Castillo-Rogez 2022). The discovery of amphibole (tremolite), chlorite (clinochlore), and serpentine (chrysotile) coexisting in a carbonaceous chondrite clast present in a ureilite breccia implies greenschist-facies metamorphism at a temperature and pressure higher than that for other CM and CI chondrites, possibly consistent with conditions in the interior of a Ceres-sized asteroid (Hamilton et al. 2020). That parent body is considerably larger than envisioned for other carbonaceous chondrites, so the meteorite likely provides insights into conditions in Ceres' deep interior. Multiple reports of the presence of dehydrated material on the surface of Ceres (e.g., De Sanctis et al. 2015; Raponi et al. 2021) might be evidence for thermal metamorphism in the mantle. However, the emplacement of that material into Ceres' regolith remains to be explained. Contamination from exogenic material that may include anhydrous or dehydrated material is another possible explanation (Marchi et al. 2019).

3.1.2. Long-term Persistence of Liquid Water in the Absence of Tidal Heating

Tidal dissipation is thought to enable subsurface liquid water and related surface activity on many solar system moons, such as Enceladus and perhaps Mimas and Dione in the Saturn system, possibly Miranda and Ariel in the Uranian system, and Neptune's moon Triton (e.g., Hendrix et al. 2019). On larger objects, such as Europa, Ganymede, Callisto, and Titan, radiogenic heating alone can maintain the subsurface oceans whose signatures were detected by the Galileo and Cassini missions, although tidal dissipation may enhance associated activity, e.g., at Europa. Ceres, which does not orbit a giant planet, never experienced any significant heating from tidal dissipation. That its interior still harbors liquid water on the verge of refreezing therefore provides information on the ability of radiogenic heating, augmented perhaps to a small extent by the heat of accretion (Bierson et al. 2020) and later impacts (Bowling et al. 2019), to sustain subsurface liquid water.

In the absence of tidal heating, the persistence of liquid water mainly depends on (a) the body's size: the ratio of heat production (scales with volume) to heat loss (scales to first order with surface area) is proportional to the radius; (b) the rock mass fraction, which determines the abundance of long-lived radioisotopes; (c) the presence of salt, hydrates, or volatile impurities that can change the interior's physical and chemical properties (freezing point, insulation, strength); (d) and to a lesser extent the heliocentric distance that largely sets the temperature at the surface (Hussmann et al. 2006). The evidence at Ceres (radius of 470 km) therefore suggests that larger worlds (radius >700 km), such as Uranus's moons Titania and Oberon, and trans-Neptunian objects such as Pluto, Eris, Haumea, and Makemake may also host subsurface liquid today. Indeed, there are hints that Pluto may harbor an ocean (Keane et al. 2016; Nimmo et al. 2016; Denton et al. 2021). On the other hand, Pluto's moon Charon, with a radius of ≈ 600 km and heliocentric distance of ≈ 40 au, seems to have fully refrozen (Desch & Neveu 2017).

An object's size and heliocentric distance are readily determined, but the crux of estimating ocean persistence in the absence of obvious surface expression or major tidal dissipation lies in understanding the feedback between interior

physical and chemical processes. The recent exploration of Ceres (and the Pluto system) has hinted at how complex such feedback may be. Salts and gas hydrates possibly affect the near-surface strength (Bland et al. 2016) and therefore the means by which heat is transferred to the surface and lost to space by convection (Formisano et al. 2020) or conduction (Kamata et al. 2019; Neumann et al. 2020). Water-rock reactions, including those able to produce Ceres' surface composition, may change the distribution of radionuclides and generate or consume antifreeze species (Neveu et al. 2017), as well as enhance or inhibit deep convection in porous rock, which tends to homogenize temperatures in the interior, keeping ice melted at depth (Neveu et al. 2015). The relative densities of the crust and subsurface fluids, which depend on their chemical composition, affect the surface expression of fluids through volcanism (Ruesch et al. 2019a). Ceres offers the opportunity to investigate how this interplay of planetary physics and chemistry affects the persistence of oceans and their surface expression, with the tidal heating variable separated out.

The energy source driving late activity in Ceres is not well understood. Long-lived radioisotopes by themselves would not be able to preserve a deep liquid layer, especially if heat travels through the crust via convection. In most models, the bulk of the ocean would freeze on a timescale of about 200 million yr. However, based on pre-Dawn models, a residual liquid layer could exist if enriched with ammonia and chlorides, which would lower the melting temperature (Castillo-Rogez & McCord 2010; Neveu & Desch 2015). Three explanations have been suggested for the existence of substantial liquid, at least locally, inside Ceres at present (Figure 3).

First, the onset of convection in Ceres' crust may have been prevented based on the inference that the crust is at least 3 orders of magnitude more viscous than water ice (Bland et al. 2016), even though its density is only slightly greater than ice. Two interpretations have been suggested: the crust is enriched in clathrate hydrates, whose thermophysical properties are consistent with these observations (Bland et al. 2016; Fu et al. 2017) and are expected to form in Ceres' early ocean (Castillo-Rogez et al. 2018), and, as an alternative, pinning of the ice grain boundaries with silicate particles could also increase the overall strength of the crust (Qi et al. 2018). The main difference between the two models is that the thermal conductivity of clathrate hydrates is also a factor of 5–10 lower than that of ice. Hence, the clathrate-rich model would lead to warmer interiors than the ice-rich crust model (Castillo-Rogez et al. 2019).

The second hypothesis for explaining the presence of liquid in Ceres at present is the release of volatiles as a consequence of thermal metamorphism in the mantle (Melwani Daswani et al. 2021; "late water release path" in Figure 3). This prospect was considered in several pre-Dawn models, but its consequences for the state of the hydrosphere were not fully modeled. The timing of that event depends on the properties of the rocky mantle, in particular its thermal conductivity, a parameter that is not well constrained. Hence, a wide range of evolution outcomes are possible. The most likely period for the onset of thermal metamorphism would be around 1 Gyr, the time at which accumulated radiogenic heat reaches a maximum before decreasing as heat transport outpaces the exponentially decreasing heat production (Castillo-Rogez & McCord 2010). Whether liquid release at the base of the crust or added to the

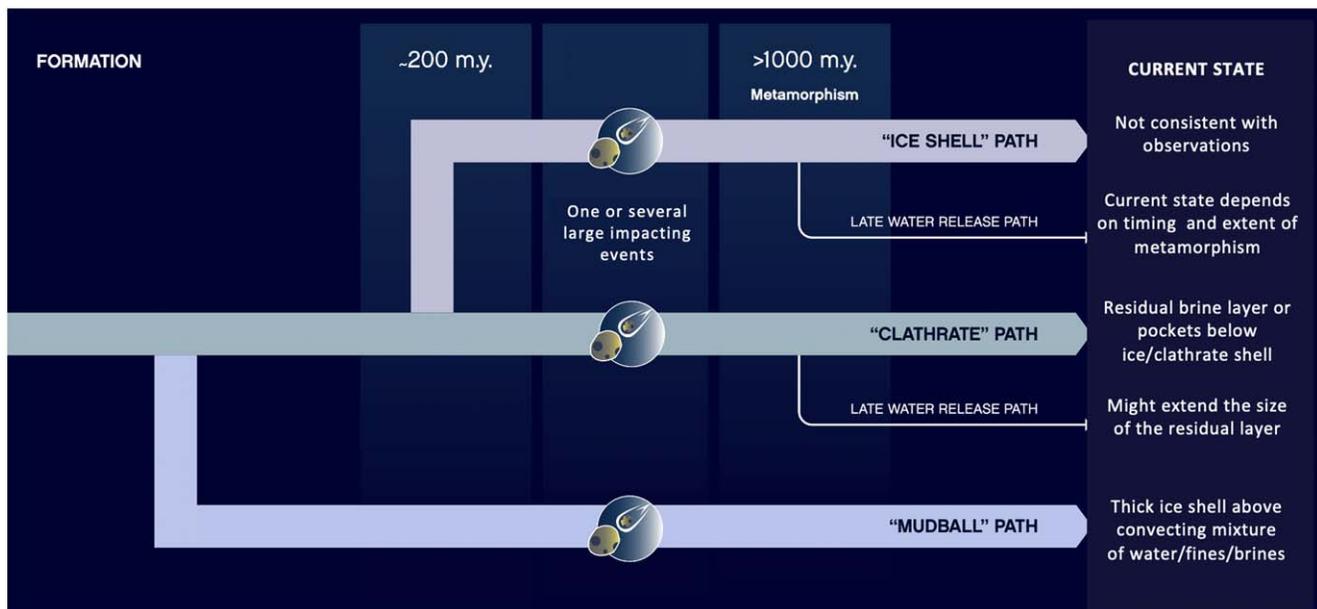


Figure 3. Possible explanations that have been suggested for explaining late activity in Ceres. All three scenarios assume a similar early evolution involving global melting from short-lived radioisotope decay heat. The “ice shell” pathway is based on pre-Dawn models that assume an ice-dominated crust that might be convecting. In those models, thermal metamorphism was expected to happen but not fully modeled. The “clathrate” pathway assumes a crust rich in clathrate hydrates or ice–rock mixtures such that the onset of convection is unlikely. That path enables the preservation of brines, with the potential addition of volatiles produced from thermal metamorphism. The “mudball” pathway assumes that Ceres’ heat transfer was driven by slow hydrothermal circulation in a thick ocean that remains at present. In that case, the mantle temperatures remain too low ($<100^{\circ}\text{C}$) for thermal metamorphism to develop. It is also likely that Ceres was subject to intensive impacting in its early history, which could have locally warmed its crust and created pathways for the extrusion of deep material.

residual ocean at the time would be preserved until present remains to be modeled.

Third, a different evolution pathway was proposed by Travis et al. (2018), whose “mudball” model assumes long-lived convection of an ocean loaded in silicate particles. In that model, a thick ocean remains until present, and the mantle temperature remains below 100°C throughout Ceres’ history. Pros and cons for that model are summarized in Castillo-Rogez & Bland (2021). The main open question is whether fine rock particles would remain in suspension for billions of years and avoid processes such as hydrolysis (Sirono 2013) and flocculation (e.g., Kranck 1973). In that model, the temperatures in the rocky mantle are too cold for the onset of hydrated rock thermal metamorphism.

On top of these global evolution models, impacts may also act in creating transient melt (e.g., Bowling et al. 2019). In particular, basin-forming impacts in Ceres’ early history (Marchi et al. 2016) likely created a significant amount of deep melt, although this process and its consequences have not been modeled.

The occurrence of clathrate hydrates in icy moons has been predicted by previous models, e.g., Titan (Lunine & Stevenson 1985, 1987) and Enceladus (Fortes 2007), but their detection remains elusive. Clathrate hydrates have been suggested as potentially being responsible for the preservation of liquid in other bodies with a limited heat budget, such as Pluto and Callisto (Kamata et al. 2019). Kalousova & Sotin (2020) showed that the presence of clathrates could result in thinning the stagnant lid of Titan’s shell, potentially favoring communication between the surface and deep interior.

The seismometry experiment planned on NASA’s Dragonfly mission (Marusiak et al. 2021) could potentially find a signature of methane clathrates in Titan’s upper shell, provided that this material is present in abundance. Similarly, a future

mission to Ceres, bringing the geophysical techniques necessary to probe Ceres’ subsurface (e.g., electromagnetic sounding; Grimm et al. 2021), could distinguish between a clathrate-rich and an ice-rich crust.

3.1.3. Chemical Evolution of Water-rich Worlds

Ceres’ small heliocentric distance relative to other largely airless water-rich objects (e.g., the icy moons of the giant planets and trans-Neptunian objects) is such that water ice is not stable at its surface. Hence, Ceres’ surface exposes products of water–rock interaction (including salts, phyllosilicates, carbonates, oxides, and volatile and organic compounds) that provide insights into chemical evolution (Section 2.1). By contrast, at other water-rich worlds, hints of non-ice compounds are instead largely diluted or masked by surface water ice, especially in the case of salts. This complicates even a first-order assessment of their chemistry unless non-ice materials are expressed in another way (e.g., the plume of Enceladus, or, for volatiles, the atmospheres of Titan, Triton, and Pluto). Moreover, some non-ice components may be products of radiation or delivery rather than reflective of planetary interior chemistry (e.g., Brown & Hand 2013).

It follows that the chemical investigation of Ceres, which has bulk properties (density $\approx 2000\text{ kg m}^{-3}$; volume-averaged radius 470 km) broadly similar to many water-rich moons and dwarf planets (densities $\approx 1000\text{--}3000\text{ kg m}^{-3}$; radii $\approx 200\text{--}2500\text{ km}$; e.g., Hussmann et al. 2006; Figure 2), provides a unique window into their water–rock chemistry. This includes an inference of the starting rocky and icy materials that these worlds accreted, the products of their interaction, and the partitioning of these products between the interior (solids and aqueous solution), surface, and outgassing.

In making such extrapolations, it is important to consider possible sources of differences in chemical evolution. A first

source is the diversity of formation conditions as suggested by, for example, the factor-of-3 diversity in bulk densities across water-rich worlds. A second is a diversity of evolution pathways linked to different dynamical environments (collisions, tidal interactions) or heliocentric distances (e.g., affecting volatile escape). Nonetheless, the broad similarity between the observed or inferred distribution of these products at Ceres relative to other water-rich bodies confirms the usefulness of Ceres in providing information about the chemistry of other water-rich worlds (Neveu et al. 2017). The variety of surface ages on Ceres (Section 2.1) facilitates an assessment of the chemical changes that occurred throughout the significant fraction of solar system history spanned by these ages.

Several processes that affect the long-term evolution of Ceres' ocean (Figure 3) are also relevant to other mid-sized and large icy moons. First, a freezing ocean concentrates solutes, leading to saturated solutions, as might be the case for Ceres. Chemical alteration could proceed to equilibrium in Ceres, after which the ocean system would become chemically nonreactive. Release of mantle volatiles to the ocean by thermal metamorphism (Melwani Daswani et al. 2021), as well as radiolysis (e.g., Bouquet et al. 2017; Altair et al. 2018), can reintroduce chemical gradients into the ocean and/or shift ocean redox and pH conditions, maintaining limited disequilibrium (Figure 4). The effect of mantle devolatilization may be small in the case of a thick ocean but could be significant in the case of a residual liquid layer, as is expected in Ceres if the brine temperature is significantly below 273 K (Castillo-Rogez et al. 2019). Lastly, large impacts could potentially reach Ceres' ocean, at least when the crust was thinner, and introduce diverse material serving as a basis for late aqueous alteration.

The composition of evaporites recently exposed on Ceres' surface would provide information about the environmental conditions of the deep brine reservoir (J. C. Castillo-Rogez et al. 2022, in press) and test whether these indicate a primary origin (residual endogenic liquid) or result instead from a second generation of liquid (e.g., impact melt) and input of exogenic material. Similar questions likely apply to other large ice-rich bodies. For example, the thermal breakdown of hydrated silicates, carbonates, and other volatile-bearing materials is expected at Europa (Melwani Daswani et al. 2021), Titan (Castillo-Rogez & Lunine 2010), Ganymede (based on the presence of a metallic core), and other icy bodies greater than ~ 500 km in radius that could build up heat from long-lived radioisotope decay. Melwani Daswani et al. (2021) showed that carbon dioxide could represent a late source of carbonates and/or clathrate hydrates in Europa's ocean. Furthermore, the thermal breakdown of nitrogen-rich organics, such as amino acids and acetamides (e.g., Nakano et al. 2020), can release ammonia that can control the solubility of carbon dioxide. Hence, carbonates could make a significant contribution to the salinity of ocean worlds (Castillo-Rogez & Bland 2021). The high abundance of carbonates in Ceres' evaporites may be a signature of this process, or they could have formed early on and concentrated in the residual ocean. In order to resolve this uncertainty, in-depth investigations of evaporites are required, in particular to obtain the isotopic ratios of oxygen and carbon that may constrain the origin of the carbonate ions in the brine reservoir and the precipitation conditions of the carbonates.

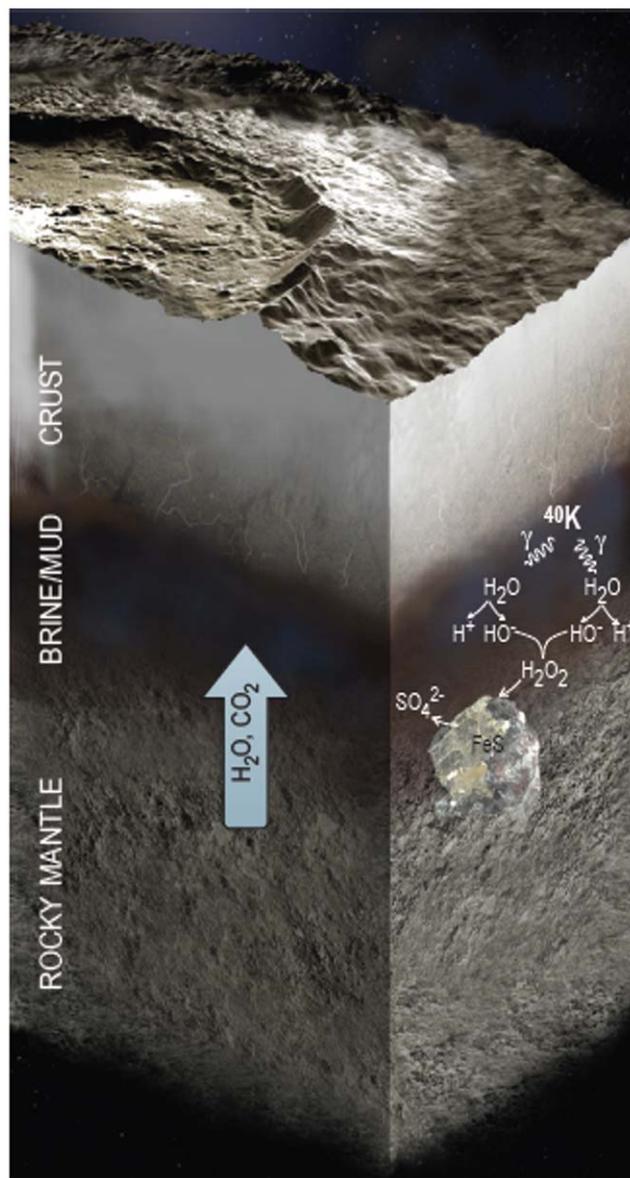


Figure 4. Summary of processes that may alter the chemical properties of a deep ocean over time: loss of volatiles from the mantle upon thermal metamorphism and radiolysis. The Occator impact itself could introduce exogenic material in the crust. Based on Altair et al. (2018); background rendering from Raoul Ranao.

3.1.4. Carbon Partitioning and the Fate of OM in Long-lived Liquid Reservoirs

The OM in carbonaceous chondrites and interplanetary dust particles presents a high diversity of several thousands of organic compounds along a structural and molecular continuum (Remusat 2015; Alexander et al. 2017). In carbonaceous chondrites, which have been more extensively studied, OM is usually divided into two fractions: (i) a soluble organic fraction (SOM), made of thousands of different small molecules (including carboxylic acids, amino acids, sugars, aliphatic, and alcohols; e.g., Schmitt-Kopplin et al. 2010), and (ii) an insoluble organic fraction (IOM), represented as a macromolecular structure composed of aliphatic and aromatic carbon units with some heteroatoms (O, N, S) showing a high degree of cross-linking (Remusat et al. 2010) associated with a more volatile aromatic fraction containing molecular diversity

(Danger et al. 2020). The diversity and abundance of OM identified to date in carbonaceous chondrites may reflect both a diversity of organic materials present in the protosolar nebula before planetary accretion (e.g., Kerridge 1999) and further enhancement via hydrothermal synthesis in chondritic parent bodies at conditions revealed in their mineral makeup (e.g., Brearley 2006). The degree of OM transformation during hydrothermal activity is a major question in astrochemistry, with implications for carbonaceous asteroids, dwarf planets, and icy moons, as well as Mars' surface. Analyses of CM chondrites indicates that the proportion of IOM in CM chondrites diminishes with increasing aqueous alteration, while carbonate abundance increases concomitantly (Alexander et al. 2015), indicating a degradation of OM. In addition, in some specific CC meteorites, such as CI, CM, CR, and the ungrouped Tagish Lake (e.g., Pizzarello et al. 2001; Pizzarello & Holmes 2009), the relative abundance of amino acids decreases with an increasing degree of aqueous alteration, indicating that this process altered the OM (Glavin et al. 2010). Alternatively, aqueous alteration might also redistribute the initial molecular composition and allow the formation of new species (Vinogradoff et al. 2017; Danger et al. 2021). In contrast, thermal metamorphism has a more destructive effect on the OM and leads mainly to the graphitization and decrease of OM diversity (e.g., Kebukawa 2011).

Laboratory studies have also shown that organic molecules (e.g., tholins, chondritic organics) are transformed in aqueous alteration experiments (Kebukawa et al. 2013, 2020; Brassé et al. 2017; Vinogradoff et al. 2018; Danger et al. 2021), producing numerous new soluble molecules and insoluble OM as a function of time and temperature. The nature and extent of OM evolution likely depends on the nature of the initial molecules, the interaction with minerals, and the fluid properties (Gil-Lozano et al. 2020; Haas et al. 2020; Vinogradoff et al. 2020). The spatial co-occurrence of OM with phyllosilicates and carbonates observed at the surface of Ceres (Raponi et al. 2017; De Sanctis et al. 2019) suggests a close genetic relationship between these phases and a possible coevolution during hydrothermal processing. Because Ceres is the first main belt object where a strong and incontestable in situ OM signature has been detected, further observations and analysis of this assemblage are of primary importance for understanding the evolution of OM in hydrothermal systems. Quantifying the extent of OM transformation in Ceres requires new observations, models, and experiments in order to better constrain the role of the abundance and types of minerals, the water-to-rock ratio, and the salinity. Developing that knowledge will also be valuable for predicting the chemical evolution of organic material in carbonaceous-rich asteroids and ocean worlds.

Observations of OM in carbonaceous chondrites reveal intimate mixing of likely soluble compounds with minerals, especially Mg phyllosilicates after hydrothermal alteration (Le Guillou et al. 2014; Vinogradoff et al. 2017). The differentiation event may have led to accumulation of OM in the rocky mantle, simultaneous with geochemical processing. Graphite, methane, and carbonates are the thermodynamically stable end-member carbon-bearing components, depending on geochemical parameters including temperature, redox state, and pH and assuming a long-lived system. Kinetics may play a role in the long-term evolution of natural carbon systems, and metastable organic compounds, such as kerogen of intermediate oxidation state (Seewald et al. 1998), may have been important carbon

reservoirs throughout most of Ceres' history (e.g., Shock & McKinnon 1993; Neveu et al. 2017).

Increased temperature can increase the solubility of organics in water, and in the presence of clay catalysts, the organics tend to be more reactive (less stable; Siskin & Katritzky 2001). On the other hand, increased brine concentration can cause chemical reactions and form complexes between organic molecules and ions that will decrease the solubility of organics. The chemistry of natural aqueous fluids is complex and can depend on the specific composition; for instance, in terrestrial systems, the Hofmeister series describes the tendency of specific ions, such as carbonate, to remove macromolecules from aqueous solution and stabilize them against reaction. The underlying mechanisms are only now being discovered with the aid of increased computational capability (e.g., Gregory et al. 2021).

Alternatively, if the system stayed cold, then even over billions of years, kinetic inhibition of degradation reactions may preserve the kerogen-like IOM. However, IOM starts to evolve at $\gtrsim 125^\circ\text{C}$, which is expected in Ceres' mantle throughout its history (Castillo-Rogez et al. 2019).

Moderate- to high-temperature organic-water reactions are consistent with observations of long-lived terrestrial fluids. Fracture fluids from the Kidd Creek mine in Canada, which have been dated to 2.6 Ga (Holland et al. 2013), may represent the best terrestrial analog for abiotic carbon chemistry in long-residence liquid reservoirs. The Kidd Creek fluids potentially represent a good analog for the upper mantle of Ceres and ocean worlds by hosting a reducing environment isolated from the more oxidizing terrestrial fluids in a rock setting that is primarily of mafic and ultramafic composition.

Sherwood Lollar et al. (2021) identified three unique characteristics for Kidd Creek fluids in comparison to other terrestrial fluids: high concentrations of formate and acetate, acetate/formate molar ratios >1 , and ^{13}C enrichment in acetate. They attributed these characteristics to abiotic organic synthesis facilitated by both metal catalysts and radiolytic production and suggested that the ^{13}C enrichment may be linked to a dissolved inorganic carbon source. In particular, they noted that the shorter residence times (1–20 Myr; Sherwood Lollar et al. 2021) and lower acetate and formate concentrations reported at Witwatersrand Basin (Onstott et al. 2006a, 2006b; Kieft et al. 2018) and the longer residence times (100–1000 Myr; Holland et al. 2013) and higher concentrations of acetate and formate at Kidd Creek are consistent with experimental radiolytic production rates for formate and acetate from carbonate and/or bicarbonate ions derived from dissolution of carbonates (Costagliola et al. 2017). Thus, radioactive decay of U, Th, and/or K may drive carbon chemistry away from thermodynamically stable carbonates toward organic acids. Such a scenario may characterize aging of carbon phases in aqueous systems.

Radiolysis may drive the environmental conditions toward more reducing conditions that eventually favor CH_4 production. Radiolysis may also contribute significantly to the production of H_2 in the rocky mantles of icy bodies (Bouquet et al. 2017). While it has been suggested that the reduction of CO_2 to CH_4 may be kinetically inhibited in conditions relevant to Ceres (e.g., McCollom 2016), the low H_2/CH_4 ratio of the Kidd Creek fluids may provide evidence for formation of CH_4 in long-lived natural systems, perhaps via metal catalysts such as iron sulfides (e.g., greigite (Fe_3S_4); Sherwood Lollar et al. 2002;

Reeves & Fiebig 2020). Such considerations have previously been used to distinguish between modern and ancient formation of H₂ at Enceladus (Waite et al. 2017). The rate of radiolysis would be highest early in solar system history; however, the long half-lives of U and Th, especially, would lead to continued significant radioactivity into the present era. Equilibrium speciation suggests that U and Th remain in mineral phases under plausible ocean world conditions (Neveu et al. 2017), while K may leach into aqueous solutions. Hydrothermal models of Ceres' interior predicted that serpentinization may cease within 2–3 Myr but that radiogenic heating would maintain a mud mantle slurry with intermixed mineral and fluid phases (e.g., Travis et al. 2018).

A future mission that would analyze the composition of salts and organic compounds found in Occator crater would help assess the state of the OM in Ceres' crust and residual ocean. The understanding of the corelation of salts and organic compounds upon precipitation, including via freezing, in conditions relevant to planetary bodies (e.g., potential flash freezing on an airless surface) is limited by a lack of experimental work and relevant terrestrial analogs, although work in this area is expanding (Buffo et al. 2020; Cockell et al. 2020; Pasek 2020). In particular, two examples of extraterrestrial halite clasts have been found in the meteorite collections (Rubin et al. 2002), whose study has revealed various types of organic compounds on a scale of a few nanometers (Chan et al. 2018). Although the origin of these clasts is unknown, they are likely representative of the evaporite material found at Ceres (e.g., Fries et al. 2014).

3.1.5. Role of Impacts in Enabling Subsurface–Surface Material Transfer

Fractures created by large impacts on Ceres' surface could tap shallow fluid pockets in the crust, as has been suggested in the case of Occator crater (Quick et al. 2019; Raymond et al. 2020; Scully et al. 2020). More generally, evidence for old evaporites has been found to be spatially associated with floor fractures at large craters such as Dantu (Stephan et al. 2018). Hence, it is likely that large impacts helped open pathways between the deep interior and the surface throughout Ceres' history. Domes found across the surface further indicate that volcanic or intrusive activity could have been a widespread process in space and time (Sori et al. 2018), but whether impact-induced fractures enabled that process is unknown. Davison et al. (2015) suggested that larger, basin-forming impacts could potentially excavate Ceres' upper mantle, which could potentially lead to regional-scale distribution of mantle material (Marchi et al. 2016).

Transfer of material within Ceres is expected to be unidirectional, helped by the fact that the residual brine layer or reservoir is likely under pressure (e.g., Neveu & Desch 2015). On the other hand, impactors could have contributed new material to the crust. Indeed, recent studies emphasized that an icy crust can retain a large fraction of impactor material. Bowling et al. (2019) modeled that up to 70 wt.% of impactor material could be embedded in the melt chamber created by the impact-produced heat. More generally, Marchi et al. (2019) showed that a large fraction of impactor material would accumulate in Ceres' outer 5–10 km. Similarly, Pierazzo & Chyba (2002) pointed out that cometary impactors could have delivered organic compounds to Europa's shell throughout the moon's history. The creation of pathways

between the deep interior and surface by impacts has also been suggested for Europa (e.g., Cox & Bauer 2015). This process was likely important in the early history of most large icy bodies with thin ice shells and under a higher flux of impactors than at present.

In summary, impacts can facilitate material transfer and introduce new material into the crust, as shown in the case of Occator crater. The redistribution of impact-induced or residual deep and crustal brines can be driven by the thermal alteration of the surface after impact, driving brines through the subsurface and toward the surface through a combination of hydrologic, topographic, and material gradients (Schmidt et al. 2020), which is common in terrestrial environments with freezing or frozen ground. Similar cryohydrologic and hydraulic formation of surface features, including shallow brine zones, has been proposed for Europa (Schmidt et al. 2011, 2020) and may be relevant for Ceres and other ocean worlds. Since the freezing of brines can chemically fractionate this potential mixture of initial and impactor material (e.g., Buffo et al. 2020, 2021; Fox-Powell & Cousins 2021), much could be learned about the drivers of chemical evolution in crustal aqueous solutions from geophysical probing of the region below Occator crater. Such probing includes visualization of its fracture network and the geometry of the residual impact melt chamber using radar techniques and electromagnetic sounding (Grimm et al. 2021).

3.2. Other Ceres Science Themes

3.2.1. Early Solar System History and Dynamical Evolution

The widespread occurrence of ammoniated phyllosilicates and carbon on the surface suggests that Ceres must have formed in a region of the solar system where primordial thermodynamic conditions allowed it to effectively accrete large amounts of nitrogen and carbon. The main asteroid belt, the interplanetary disk between the orbits of Jupiter and Neptune, or the Kuiper Belt, located beyond the orbit of Neptune, can be considered possible locations of formation, assuming that Ceres (or the materials from which Ceres formed) then migrated to its present-day position.

The Jupiter–Saturn region has been proposed as the source of most C-type (carbonaceous and hydrated) asteroids and may represent Ceres' most likely formation region (e.g., Raymond & Izidoro 2017; Raymond & Nesvorný 2020). Recently, the possibility that the core of Jupiter itself may have formed further from the Sun and then migrated inward has been proposed, dragging with it a multitude of minor bodies (Bosman et al. 2019). The overabundance of elemental nitrogen measured in Jupiter's atmosphere with respect to the protosolar value (Atreya et al. 2018) implies that the planet's core must have formed outside or just inside the N₂ ice line (Bosman et al. 2019; Öberg & Wordsworth 2019). The position of the latter is difficult to quantify in the primordial solar system, but it is of the order of a few tens of astronomical units, which would, moreover, point toward a pebble accretion or gravitational instability origin for Jupiter (Bosman et al. 2019). Alternatively, amorphous ice with adsorbed volatiles may have drifted inward to enrich the gaseous phase of the protosolar nebula with elements such as nitrogen once this ice complex crossed the amorphous ice snow line (i.e., the amorphous-to-crystalline ice transition zone; Mousis et al. 2019).

The rapid formation of Jupiter likely destabilized the orbits of nearby planetesimals. Under the action of the aerodynamic drag due to nebular gas, a fraction of the planetesimal population was deposited into stable orbits inside Jupiter's (e.g., Grazier et al. 2014). This process is effective in populating the main outer belt with C-type asteroids that originated from a large region (5–20 au) of the disk (Raymond & Izidoro 2017). However, this scenario implies that we should find many other small bodies in the asteroid belt with a composition similar to Ceres, whereas Ceres' bulk composition is atypical compared to C-type asteroids, with the possible exception of 10 Hygiea and a few other ≥ 100 km large asteroids (Rivkin et al. 2019). A possible explanation for this apparent paradox is that conditions in large asteroids favored aqueous alteration that led to the formation of ammoniated minerals and carbonates that display distinct signatures in the infrared. On the other hand, smaller bodies lost ammonia and carbon mono/dioxide ices that are not stable on the surfaces of airless bodies. Another explanation for the scarcity of Ceres-type bodies in the asteroid belt may be that Ceres underwent a certain degree of pebble accretion before being scattered inward. Because the efficiency of this process is directly proportional to the size of the planetesimal (Johansen et al. 2015), a primordial body the size of Ceres could have grown more volatile-rich from pebbles that originated in the outer solar system than similar bodies of smaller size (Kretke et al. 2017).

A competing origin for the high abundance of ammonia found at Ceres is that it was released from the metamorphism of organic compounds (McSween et al. 2018). Experimental work by Pizzarello & Williams (2012) and Nakano et al. (2020) suggests that pressures of tens of megapascals and temperatures of a few hundred degrees Celsius are sufficient to drive organic breakdown in a few hundred kiloyears, and these conditions could have prevailed in Ceres' mantle for at least 1 Gyr (Castillo-Rogez & McCord 2010).

In summary, the origin of Ceres is a major open question with fundamental implications for the origin of volatiles and OM in the inner solar system (e.g., Budde 2019), the mechanisms driving the solar system architecture, and the role that large planetesimals could have played by impacting the growing planets (e.g., Canup & Salmon 2018). Castillo-Rogez et al. (2020) pointed out that analysis of returned material from Ceres in Earth-based laboratory facilities is the best approach to resolving the origin of Ceres because the complex and evolving chemical and dynamical framework describing the early solar system necessitates adaptability in the measurements to be carried out and because of additional complications specific to dealing with a very large planetesimal (e.g., pebble accretion, alteration during evolution).

Testing Ceres' potential genetic relationship with the Galilean moons, either from sharing the same accretional environment or from representing the building-block population that contributed to the Jovian circumplanetary disk, should be a high-priority objective of a future mission to the dwarf planet. If that relationship is confirmed, then Ceres' geochemical evolution will be particularly informative about the evolution of those moons.

3.2.2. Ceres as a Natural Laboratory to Study Geological Processes in an Ice-rich Crust

Geological history is well recorded on Ceres relative to resurfaced worlds like Europa. Ceres may also represent an

advanced, less active state of worlds than those exemplified by Europa; thus, Ceres represents a major end-member on the varied spectrum of icy objects. Therefore, Ceres may serve a role in our understanding of icy worlds analogous to that of the Moon in our understanding of terrestrial planets.

As a result of Ceres' special role in our understanding of icy worlds, many icy geological processes that operate throughout the solar system would be elucidated by further study at Ceres (Figure 5). Cryovolcanism has likely been an important process of interior–surface exchange on a number of icy worlds (e.g., Enceladus; Spencer & Nimmo 2013). On Ceres, brine-driven effusion has been proposed as the best explanation for the origin of the Occator faculae (Figures 5(a) and (b); e.g., Scully et al. 2020) and Ahuna Mons (Figure 5(c); Ruesch et al. 2019a). The underlying mechanism driving volcanic-like activity on Ceres is not fully elucidated. As in the case of icy moons, the low contrast between Ceres' crust ($\sim 1.1\text{--}1.3\text{ g cm}^{-3}$) and brine densities ($1.2\text{--}1.3\text{ g m}^{-3}$; Quick et al. 2019) is not favorable to brine upwelling. The situation is even more problematic if a large amount of mud is involved, as inferred in the case of Ahuna Mons (Ruesch et al. 2019b). Possible explanations include upwelling assistance from the pressure generated in a residual brine reservoir (Neveu & Desch 2015) released by fractures introduced by impacts, potentially helped by a high content of dissolved volatiles (e.g., CO_2 ; Quick et al. 2019). Convection and diapirism have been invoked in the case of Ahuna Mons (Ruesch et al. 2019a). Some of these processes likely apply to other bodies, for example, Pluto, Enceladus, and Europa (Manga & Wang 2007). A key difference is that most ocean worlds likely host thick oceans, so that cryovolcanism on these bodies involves low-salinity liquid and few to no silicate particles suspended in the ocean.

Geophysical analysis of icy crustal structure has been performed on Ceres with more precise data than on any other icy object (Park et al. 2020) but still lags far behind our knowledge of the crusts of rocky worlds like Earth, the Moon, and Mars. Tectonic processes likely also occur on Ceres (e.g., Bland et al. 2019; Ruiz et al. 2019), although the mechanisms involved are not well understood. Geologic processes on Ceres including extensional tectonics (Figure 5(i); Hughson et al. 2018), landslides, and other material flows (Figures 5(d)–(f); e.g., Schmidt et al. 2017; Hughson et al. 2019), as well as cryohydrologic features (Figure 5(g); Schmidt et al. 2020), may involve a mixture of silicates, ice, and water common to glacial environments on the Earth and Mars. Other authors (Johnson & Sori 2020) have argued that mass-wasting features on Ceres do not inform us about local ice content or shallow compositional structure and instead are strongly controlled by topography. What is clear is that Ceres, especially when jointly analyzed in a comparative fashion with rocky planets, holds promise for elucidating which surface processes are unique to icy worlds and which are common to many types of objects. Despite Ceres' similar surface gravity to the asteroid Vesta, Dawn observed a wide diversity of landslides and material flows on Ceres that were not present on Vesta, which suggests a fundamental difference in the composition of their near surfaces (Schmidt et al. 2017). These include long-runout landslides, low-mobility viscous flows (Figure 5(d) and (e)), and ejecta that appears to be fluidized (Figure 5(f)). The mobility regimes of these observed mass movements suggest that the crust is an intimate mixture of rock and ice that can

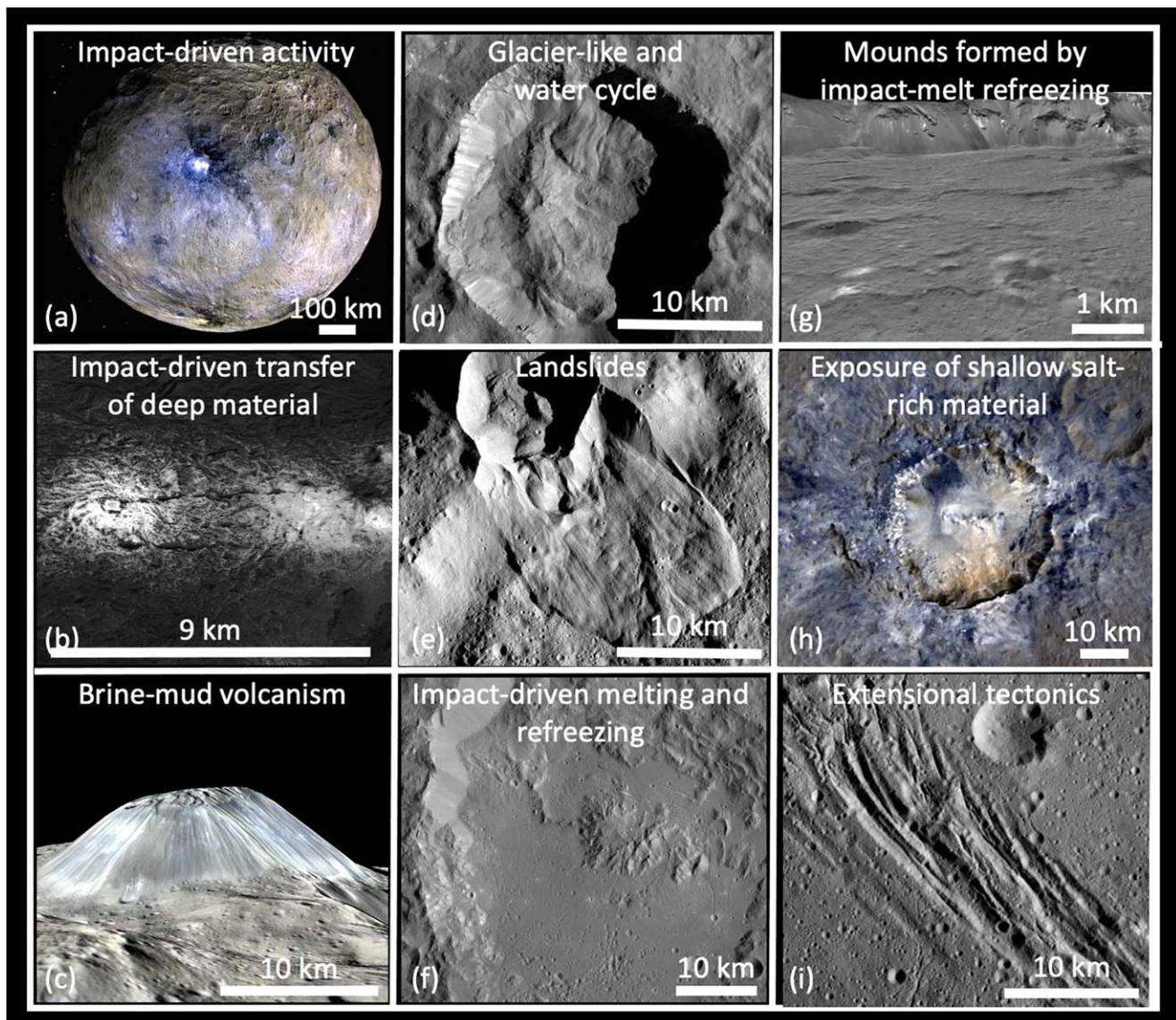


Figure 5. Examples of landforms found at Ceres that make it a natural laboratory to study geological processes in an ice-rich crust. (a) Recent evaporite exposure in Occator crater; (b) brine exposure via fractures in Vinalia Faculae, in the eastern part of Occator crater; (c) Ahuna Mons, a cryovolcano built with rock and brine (Ruesch et al. 2016, 2019a), as indicated by the high content of sodium carbonate (bright bluish material) on its flanks (Zambon et al. 2017); (d) glacier-like features in Juling crater (Raponi et al. 2018); (e) landslide whose morphology indicates a high ice content (Schmidt et al. 2017); (f) flat floor resulting from impact-generated heat and melting in Ikapati crater; (g) (forefront) mounds and hills formed from postimpact cryohydrologic processes (Schmidt et al. 2020); (h) fresh salt-rich ejecta (dark blue material) and central crest in Haulani crater (Tosi et al. 2018); (i) normal faulting in an ice-rich crust at Nar Sulcus in Yalode crater (Hughson et al. 2018). Credit: NASA/JPL-Caltech/UCLA/MPS/DLR/IDA/USRA/LPL, based on PIA22090, which contains detailed information on the origin of these pictures.

behave in both viscous and inviscid manners, depending on the degree of melting and strain rate (Schmidt et al. 2017; Hughson et al. 2018). Additionally, high-resolution imagery and terrain models from Dawn’s final extended mission revealed an abundance of small quasi-conical hills on the floor of Occator crater (Figure 5(g)). These hills appear unrelated to mass wasting and secondary craters, superpose crater floor geologic units, and appear morphologically similar to cryohydrologically derived hills on Earth known as pingos (Schmidt et al. 2020). This suggests that impact cratering on Ceres can create long-lived hydrologic systems capable of circulating water and solutes that are relevant to understanding past and present habitability near the surface of airless icy worlds. Further study of these material flows and potential hydrologically derived hills has implications for the composition of Ceres, the mechanics of ice–silicate mixtures, planetary hydrology, and

habitability and thus represents an opportunity to explore multiple understudied processes relevant to icy ocean worlds.

Impact cratering, one of the dominant geological processes in the solar system, has been shown to result in similar crater sizes and morphologies on Ceres as on other icy bodies (Hiesinger et al. 2016; Schenk et al. 2021). Thus, Ceres holds promise for more detailed study of impacts into icy targets; a detailed comparative study can be found in Schenk et al. (2021). We emphasize here the need to better quantify the modifications introduced to the crust (partial melting, porosity, exogenic material, structural heterogeneities) by large impacts that are relevant to all icy bodies. As noted above, some of the implications of impact processing could be dramatic, for example, by creating transfer pathways between the surface and interior and weakening the crust, which could alter the modalities of heat transfer. Although much larger than Ceres,

Europa is also expected to have a relatively thin crust (tens of kilometers; e.g., Howell 2021); hence, better understanding the modalities of crustal breaching is of interest there as well.

Impact-derived fractures providing conduits and mixing of impact-induced melt with deeper endogenic brines could also allow oceanic material to reach the surfaces of other large icy bodies. The melt chamber and fractures formed by the Occator impact reached and mixed with deep brine reservoirs and consequently sourced materials that would otherwise not have reached the surface. Similar processes to those observed at Occator could occur on the icy satellites and other large icy bodies (e.g., dwarf planets and large KBOs); impact-derived fractures could form conduits, and merging of impact-derived and preexisting reservoirs, including deep oceans, could mix materials originating from different depths, thus enabling their emplacement on the surface and detection/investigation by space missions. This connection, as put forward in Scully et al. (2020), is related to the idea of the Manannán impact crater on Europa proposed by Steinbrügge et al. (2020).

Finally, analysis of the Dawn data raised the question of the level of exogenic inputs to the surface and shallow subsurface of water-rich airless bodies (Vernazza et al. 2017; Marchi et al. 2019). This topic is critical because the introduction of exogenic material into the crust, especially if it also involves impact melt, carries the potential to significantly alter the upper crust composition. This topic is relevant to icy moons, especially those whose power budget is too limited to sustain long-term geological activity and resurfacing. Surface coating by exogenic material has been demonstrated at Iapetus (Buratti & Mosher 1995) and is suspected to be responsible for the dark albedos of Callisto and Ganymede (Bottke et al. 2013; Cartwright et al. 2020). Late impacts into these bodies could have created local and transient pools of melt involving carbonaceous material. A better understanding of the characteristics of these microenvironments is needed, building on the Dawn results, in order to predict signatures that may be revealed by the Europa Clipper and JUICE missions.

3.2.3. Ceres as a Natural Laboratory for Understanding Processes Affecting Airless Bodies

Transient atmospheres and exospheres of airless bodies are known on Mercury, the Moon, and some icy moons of the outer solar system. These are caused either by an interaction of the space environment (meteorites, radiation) with the surface or by endogenic processes. Thus, a systematic study of these phenomena can reveal important clues on the nature of surfaces and subsurface geologic processes.

Water-ice sublimation due to solar irradiation and solar wind particle bombardment is a possible mechanism for Ceres' weak exosphere (e.g., Landis et al. 2017). Some of the released water molecules can be recaptured in permanently shadowed polar depressions, leading to thin ice deposits (Platz et al. 2016; Schörghofer et al. 2016). In addition, endogenic sources of various molecules (H_2O , CH_4 , CO_2) are conceivable (Nathues et al. 2017). Cryovolcanic processes, as suggested for Occator crater (e.g., Nathues et al. 2020), could be responsible for the development of a transient exosphere composed of different molecules and particles. Thus, Ceres is expected to be an ideal target to characterize the exosphere or transient atmosphere of an airless body. However, the search for these features has proved difficult. While a thin OH exosphere was concluded from observations of the International Ultraviolet Explorer by

A'Hearn & Feldman (1992), other studies using ground- and space-based telescopic data could not confirm its existence (Rousselot et al. 2011; Roth et al. 2016; Roth 2018). Küppers et al. (2014) reported occasional water vapor from spectral data of the Herschel Space Observatory. Further evidence of a transient Cerean atmosphere was derived from observations of Dawn's Gamma Ray and Neutron Detector upon arrival at Ceres (Villarreal et al. 2017), likely correlated with solar activity. However, since the Dawn payload was not designed to detect an exosphere or a thin atmosphere, their density and composition are still largely unexplored today.

Exposed water ice, which could be a possible source for an exosphere, was detected at several sites (Combe et al. 2016, 2019); even a seasonal variation of ice exposure in the Juling crater was reported by Raponi et al. (2018). In addition, high phase angle imaging with the Dawn Framing Camera revealed an unusual light-scattering behavior associated with the Occator faculae. This unique light scattering was attributed to an additional component to the solid surface, i.e., an optically thin and near-surface haze layer (Nathues et al. 2015, 2019; Thangjam et al. 2016). The hydrohalite detected by De Sanctis et al. (2020) at Cerealia Tholus is a possible source for the ongoing production of water and haze. The database on exospheric observable effects, events, and sources at Ceres is still sparse and requires follow-up observations to derive radial density distribution, composition, and flux rates.

4. Approaches to the Future Exploration of Ceres

This section addresses approaches to further the exploration of Ceres with future spacecraft but also via theoretical and experimental research, field work at terrestrial analogs, and Earth-based observations.

4.1. Future Missions

A future mission to Ceres could address open questions about Ceres' past and current habitability potential and some of the aforementioned processes in greater depth. Direct surface access of material evolved from the deep brines provides a unique opportunity to investigate the evolution of long-lived oceans. A recent study developed under NASA's Planetary Mission Concept Study (PMCS) program showed that significant progress in our understanding of Ceres as an evolved ocean world requires resources offered by NASA's New Frontiers and Flagship programs (J. C. Castillo-Rogez et al. 2022, in press). The PMCS study identified two mission architectures that can address a majority of the science questions listed above under a New Frontiers cost cap: a sample return from an evaporite-rich site in Occator crater or a hopper that explores the evaporites and an additional site (Figure 6). Both concepts include an orbital phase for landing site selection and certification prior to high-precision landing. For little additional cost, the orbiter can accommodate high-resolution imaging and gravity measurements at a handful of sites of interest to address past and current activity. Landed investigations are required for interior probing and compositional analysis either via sample return or using a combination of instruments for elemental, mineralogical, and isotopic measurements of evaporites and floor (nonevaporite) material. Electromagnetic sounding was identified as the most promising approach for probing Ceres' interior for deep brine distribution (Grimm et al. 2021).

analyses of the morphologies of ejecta deposits, debris flows, structures, and constructional features on Earth, Mars, Ceres, and icy moons would elevate the state of knowledge altogether.

Theoretical and experimental research. Future exploration of Ceres would benefit from work on terrestrial and laboratory analogs with a focus on better understanding the physics and chemistry of brines, OM, and mud mixtures in mid-sized bodies, which are emerging topics of importance to ocean worlds. Specific support for the following studies is recommended: laboratory research on salt clasts present in meteorite collections, which have been suggested to come from Ceres or a Ceres-like body (e.g., Chan et al. 2018); thermophysical properties of brines, hydrated salts, and clathrates; mechanical response of evaporites to impacts, a key input to deriving the faculae model ages based on crater counts, which is key to many science drivers; the effect of radiolysis in the creation of redox gradients in ocean worlds, for example, to understand the efficiency of this process and its potential to create local habitable zones; irradiation processes (ion, UV) that modify the infrared signatures of minerals and organic compounds; the behavior of brine and mud mixtures in zero-pressure surface environments at Ceres temperatures, e.g., flow properties such as fluid-rich debris flows and impact ejecta; devolatilization processes of the evaporites in a vacuum for water budget and evaporite deposit age estimates; experimental simulation of brine/organic/mud convection to inform the understanding of thermal evolution and material transfer in the interiors of mid-sized icy bodies; and synthesis and characterization of analog materials to provide comparison data sets at appropriate conditions for Ceres' surface and support the definition and development of new instruments, e.g., to investigate organic carbon in mud and/or salt mixtures.

Work on terrestrial analog sites. Geomorphological and first-order geochemical analog sites for regions of interest on Ceres exist throughout the solar system, especially on Earth and Mars. Of specific interest are soda lakes (Castillo-Rogez et al. 2020), hydrothermal systems, landslide and ejecta deposits, salt domes and other salt tectonics structures, and periglacial features such as rock glaciers, protalus lobes, and pingos (Schmidt et al. 2017, 2020). Potential analog sites on Earth can be used for testing relevant planetary instruments, surveying strategies, and sampling systems required for future missions to Ceres. This is particularly relevant for landed assets, where little is currently known about the submeter-scale geology and physical properties of the surface.

Periglacial environments on Earth are also scientifically interesting analogs for various locations on Ceres because of its inferred subsurface ice content (e.g., Prettyman et al. 2017) and myriad surface features whose morphologies suggest an icy origin (e.g., Schmidt et al. 2017, 2020; Hughson et al. 2019). Beyond the magnetotelluric sounding identified in the PMCS to investigate Ceres' deep subsurface (Grimm et al. 2021), techniques such as ground-penetrating radar and frequency- and time-domain electromagnetic sounding could further reveal Ceres' shallow stratigraphy. Deploying these techniques in analog periglacial environments would enhance the interpretation of future electromagnetic geophysical results from Ceres (e.g., <https://schmidt.eas.gatech.edu/pingo-starr/>). While glaciers and ice sheets have been extensively subjected to geophysical investigation, more Ceres-like analogs, such as protalus lobes, alpine tundra, and pingo-covered landscapes, have remained relatively understudied. Understanding how

electromagnetic systems respond in both evaporitic and periglacial environments, as well as a deeper geophysical understanding of periglacial systems on Earth, is critical for preparing for landed geophysical exploration of Ceres.

Ground-based observations. Telescopic observations from Earth or near-Earth space should continue, for example, to address the following questions: (a) the origin of Ceres' sporadic outgassing activity with regular (perihelion and seasonal) and reactive observations following the release of solar energetic protons (Villarreal et al. 2017) and (b) additional constraints on Ceres' surface composition from observations in the ultraviolet (e.g., Hubble Space Telescope) and mid-infrared wavelengths (e.g., James Webb Space Telescope Mid-InfraRed Instrument), which are complementary to the 0.4–5 μm range observed by Dawn. The next generation of space telescopes could also revolutionize the study of Ceres. The Large UV, Optical and InfraRed Surveyor mission (LUVOIR), a 15 or 8 m primary space telescope being considered for selection by the 2020 astrophysics decadal survey, made the case for further spatially resolved imaging (11–20 km pixel⁻¹) and spectroscopy (tens of kilometers) of the surface of Ceres. The high spectral resolution of LUVOIR or similar telescopes across the UV-to-near-IR wavelength range would allow global studies of Ceres' composition and searches for outgassing in the UV (LUVOIR Team 2019).

5. Conclusions

Ceres is a rich destination that displays evidence for features pertinent to ocean world science, such as forms of brine-driven effusion, OM, geological processes, impact melt, etc. It is also the closest large ice-rich object to Earth, accessible for in situ exploration and/or sample return under a New Frontiers- or small Flagship-class cost cap because of its relatively low gravity. Sampling freshly exposed evaporites would provide insights into the chemical and physical properties of a long-lived brine reservoir and test hypotheses of interest to ocean worlds, such as the prospect of late enrichment of a residual ocean in volatiles released from the mantle and radiolysis as a long-term chemical energy source for life. Long-lived activity in Ceres requires processes or crustal properties that remain to be confirmed but are expected to also apply to other dwarf planets and icy moons. More generally, Ceres might be the first example of a “muddy” ocean world, a class of bodies that might be frequent among mid-sized icy bodies whose hydro-spheres may be presently frozen but whose mantle porosity has been filled in with brines throughout most of the dwarf planet's history. Processes known to occur in Earth' sediments, such as organic chemistry or radiolysis, are presumably relevant, and their occurrence in Ceres may be tested in future exploration.

Per its high content of nitrogen and carbon, Ceres (or at least the materials from which it formed) is suspected to originate from the outer solar system, although competing hypotheses remain. Resolving this question is fundamental to firmly anchor our understanding of early solar system evolution and the origin of water and organics in the inner solar system. Hence, determining Ceres' origin, the relationship of its volatiles and organics to other inner and outer solar system bodies (icy moons and other dwarf planets), and implications for solar system dynamical evolution are additional drivers for the future exploration of Ceres (Figure 7).

Several recent mission concepts have independently emphasized science objectives that include a quantification of Ceres'

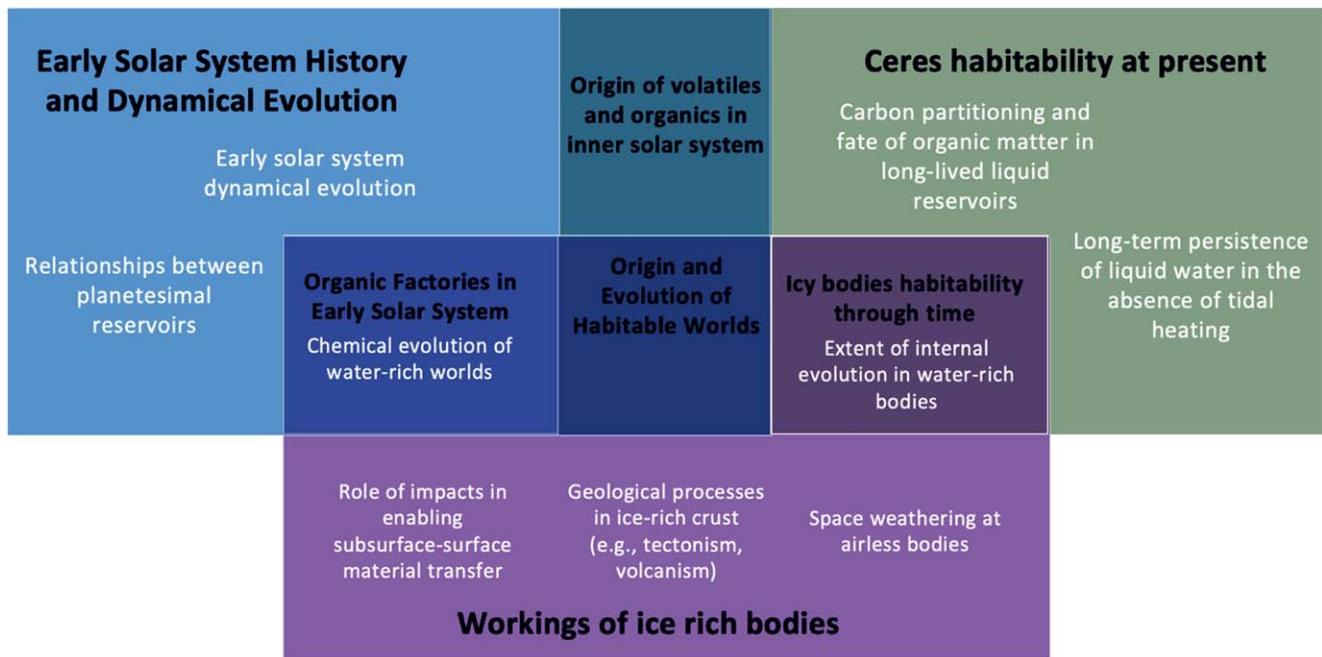


Figure 7. Summary of the science themes addressed by the exploration of Ceres. The themes are presented along with the science priorities in NASA's Planetary Science Decadal Survey (National Research Council 2011). Synergies between science themes refer to high-priority questions, such as the origin of volatiles and organics in the inner solar system and the habitability of large icy bodies through time. A future mission to Ceres should aim to address questions that pertain both to the origin of the current architecture of our solar system and to the habitability of icy bodies through time. These themes are also relevant to the search for habitable worlds in exoplanetary systems.

past and current habitability and use Ceres as a test case for unraveling the habitability over time of volatile-rich bodies. The Ceres PMCS concluded that significant progress along the Roadmap to Ocean Worlds (Hendrix et al. 2019) can be achieved with in situ exploration, either at multiple sites or at a single site and with a sample return. However, only a sample return mission can fully retire questions about Ceres' origin and the habitability potential of its residual brines. A mission returning a sample from Ceres' evaporites would address cross-cutting astrobiology goals pertinent to ocean worlds and is also being recommended by independent groups (Burbine & Greenwood 2020; Gassot et al. 2020; Shi et al. 2021).

Supporting scientific work in the form of experimental research on Ceres material analogs, ground-based telescopic observations, and continued analysis of the Dawn data is needed to further increase the science return from the Dawn mission and pave the way for follow-up exploration. Lastly, a future mission to Ceres that would optimistically kick off in the mid-2020s and return a sample by 2045 requires the participation of a diverse, inclusive, and thriving community.

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