PHYSICAL AND CHEMICAL FEEDBACKS IN LARGE ICY BODIES – LESSONS LEARNED FROM DAWN AT CERES.

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Introduction: With 22wt.% of water, the dwarf planet Ceres is representative of large icy bodies. Such bodies were subject to pervasive ice melting early on, due to short-lived radioisotope decay and/or accretional heating. They are expected to have undergone aqueous alteration, the extent of which depends on the temperature reached in the ocean and other environmental parameters such as pH and redox conditions. Salts have been found at most large icy bodies, which reflects the leaching of certain elements from the rock, such as alkali and alkaline earth metals during that period of aqueous alteration. The Dawn mission has returned extensive observational evidence for advanced aqueous alteration and chemical differentiation of the dwarf planet Ceres [1, 2, 3]. Important implications of leaching include displacement of a fraction of the potassium from the rock phase to the hydrosphere [4, 5] and the sequestration of the iron and other metals in oxides and sulfides [e.g., 5, 6]. Chemical alteration also impacts thermophysical properties and introduces new materials (salts, potentially clathrate hydrates) in the shells of icy bodies [6]. While these phenomena are potentially significant, they have not been integrated into interior models in a self-consistent manner. This work quantifies chemical differentiation and its impact on the physical evolution of Ceres, within the observational constraints returned by the Dawn mission.

Observational Constraints: The Dawn mission has returned important constraints on the interior of Ceres, showing that it is differentiated into a rock-dominated mantle and a volatile-rich shell with density ~1300 kg/m^3 [7] that encompasses the bulk of the original ocean [8]. The detection of ammonium in the clays [1] indicates removal of potassium from the silicates. The crust is stronger than ice by more than three orders of magnitude, which suggests a large fraction of hydrates [8, 9], consistent with geochemical models [6]. Hence it is likely Ceres' icy crust is a mixture of ice, clathrate hydrates, salts (including carbonates), organics, and phyllosilicates, as well as some macroporosity. A rocky mantle density of about 2430 kg/m^3 [7] has been interpreted to be of chondritic origin and subjected to a mild thermal evolution [8]. Organics have been found in a few places [10] and are believed to be of internal origin. A majority of soluble organics found in carbonaceous chondrites are mobile and would eventually be stored in Ceres' crust.

Approach: This work combines geochemical modeling with the *Geochemist's Workbench, PHREEQC,* and *FREZCHEM* [5, 11]. A major process not properly approached at present is the quantification of the extent of aqueous alteration in any object. Observations of Ceres indicate that alteration was rather advanced as illustrated by the abundance of Mg-serpentine and carbonates [1, 12]. However, in absence of constraints on the state of the iron, it is not possible to conclude that the conditions in Ceres' early history led to chemical equilibrium.

Key Results: While aqueous alteration processes occurred during Ceres' first 100 My [13], the resulting thermal conductivity structure and redistribution of potassium predicted by geochemical modeling can explain the long-term preservation of temperatures above the eutectic temperatures of chloride brines, consistent with Dawn's observations [8]. In these conditions, core temperatures remain below silicate dehydration temperatures, also consistent with observations [8]. Geochemical modeling indicates a small offset between the observed and modeled rocky mantle densities, which might point to a small (<10%) fraction of porosity consistent with the modeling of cooling cracks and other processes expected during Ceres' evolution [14]. These observations and interpretations carry important implications on the evolution of other large icy bodies, in particular Europa. Preliminary estimates suggest chemical fractionation could prevent Europa's rocky mantle from reaching temperatures hot enough for silicate dehydration and differentiation of a metallic core.

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