EVOLUTION OF LARGE VOLATILE-RICH BODIES: NEW INSIGHTS FROM CERES. J. Castillo-Rogez, C. A. Raymond, T. H. Prettyman, H. Y. McSween, O. Ruesch, R. Fu, G. Mitri, A. I. Ermakov, M. C. De Sanctis, M. Toplis, E. Ammannito, M. Neveu, C. T. Russell, Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 91109, USA, 2Planetary Science Institute, Tucson, AZ, USA, 3University of Tennessee, Knoxville, TN, USA, 4Oak Ridge Associated Universities, NASA Goddard Space Flight Center, Greenbelt, MD, USA, 5Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY, USA, 6Laboratoire de Planetologie et Geodynamique, Universite de Nantes, France, 7Istituto di Astrofisica e Planetologia Spaziali, Roma, Italy, 8Institut de Recherche en Astrophysique et Planetologie, Toulouse, France, 9UCLA, Earth, Planetary and Space Sciences, USA, 10SESE, Arizona State University, AZ, USA (Corresponding Author: Julie C. Castillo@jpl.nasa.gov)

Introduction: The role of hydrothermal activity in altering the petrology of large volatile-rich bodies was suggested in the 80’s [1], yet the many implications of water and redistribution of elements upon leaching has been barely investigated. The fractionation of long-lived radioisotopes, especially potassium [2], between the rock and volatile phases and the formation of an outer shell enriched in salts and clathrates as an outcome of differentiation [3, 4] can dramatically impact thermal evolution. With its extensive compositional, geological, and geophysical characterization of Ceres, Dawn is providing the first detailed view of a body that has been subject to advanced aqueous alteration. The integrated analysis of these datasets is revealing a picture that contrasts with pre-Dawn predictions. New knowledge gained from Ceres will help better understand the feedbacks between chemistry and geophysics in large icy satellites.

Lessons Learned at Ceres: Two reviews of what Dawn learned at Ceres will be presented at this meeting [5, 6]. A key result of the Dawn mission is the discovery of surface materials that have been subject to advanced aqueous alteration on a global scale [7, 8]. This is expressed by the presence of Mg-serpentine on top of ammoniated clays [7]. In less altered bodies iron-serpentine (cronstedtite) is the dominant form of phyllosilicate [9]. Ceres’ surface material is akin to CI chondrites to some extent [10], however the latter do not contain ammoniated silicates such as those observed at Ceres. Chondrites were formed in smaller bodies where hydrothermal circulation was impeded by the low permeability of a fine-grained matrix [11]. Gravity and GRaND observations [12, 13] are both consistent with physical and chemical fractionation, probably driven by hydrothermal circulation. A key result coming out of multiple independent studies is a density estimate of the crust between 1.4-1.6 g/cm³ [14, 15, 16]. This relatively high density may point to the enrichment of the crust in salts formed from the extensive chemical fractionation that leached alkali and alkaline earth metals from the silicates, as well as the presence of silicate particles.

Feedback Between Chemistry and Physical Processes: The thermophysical properties of alteration products significantly differ from anhydrous materials. For example thermal conductivities are generally lower, sometimes by several orders of magnitude in the case of salts and clathrate hydrates. We present a new thermal evolution model of Ceres (Figure 1) that assumes an early event of hydrothermal processing at the global scale, triggered by 26Al decay heat. That model also assumes Ceres lost its icy shell as a consequence of sublimation accelerated by impacts [17].

Nature and Evolution of the Icy Crust: The release of methane upon reaction of accreted CO₂ and hydrogen released by serpentinization has been suggested for many volatile-rich bodies [18] and has also been predicted from geochemical modeling of Ceres [19]. Dawn’s observations might be the first to bring at least indirect evidence for the large-scale occurrence of clathrate hydrates in Ceres’ crust. This is the only explanation so far for the high-strength, low-density crust inferred from topographic relaxation modeling [14, 20]. Methane destabilization upon impact heating and material removal (depressurization) might provide a means to drive buoyancy and promote the emplacement of the large mountains or domes that are interpreted to be of cryovolcanic origin [21, 22]. The depressed thermal conductivity and the concentration of 40K combine to preserve mild temperatures in the crust around 245 K, which crosses the eutectic temperatures for the chlorine-based salt solutions expected in Ceres [19] allowing for the existence of a brine reservoir at present a few tens of km below the surface.

Evolution of the Rocky Mantle: Multiple reservoirs of potassium have been suggested from geochemical modeling: in the form of salts, clays, and in supersaturated brine accumulating in a residual ocean [19, 23]. The redistribution of a fraction of 40K from the rock to the lower-density crust precludes a late phase of differentiation (e.g., dehydration and melting) of the rocky mantle. Convection in that mantle is unlikely to proceed at any time during Ceres’ evolution due to the weak temperature


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Figure 1. Thermal evolution modeled for Ceres starting at 100 Ma after formation, assuming the icy shell has been removed (see [17]). The petrological sketch presented on the right assumes the ice shell froze as a mixture of clathrates, sodium bicarbonates, and salts, based after FREZCHEM modeling. Thermal modeling yields the position of the eutectic (red curve) for the chloride species derived from that modeling, indicating the depth below which a few percent melt (brine) may exist. Residual liquid enriched in halite and ammonia might accumulate at depth. The mantle is assumed to be chondritic in nature, consistent with gravity and topography data. The long-lasting warm temperatures at >70 km depth are explained by the insulating properties of hydrated materials (with respect to pure ice and anhydrous rock).

gradient and high compressibility of phyllosilicates. Differentiation of a metallic core is precluded in these conditions. However concentration of dense, metal-rich particles at depth has been predicted [24] and supported by the analysis of measurements by the Gamma Ray and Neutron Detector [24]. Additional processes may affect the long-term evolution of the mantle: e.g., salt precipitation acting as cement, development of cracks upon cooling, etc. [25].

**Fate of Organics in Ceres:** Few organics have been found at Ceres, except for those in the region of the Ernutet crater whose origin remains to be determined [26, 27]. Under advanced alteration soluble organics may evolve into graphite [23]. Insoluble organics of densities between 1.5-2.5 g/cm³ may be stored at the interface between mantle and crust. These are mobile at the temperatures predicted by the new thermal evolution models of Ceres and their fate needs to be investigated.

**Applications to Large Volatile-Rich Bodies:** The chemistry inferred at Ceres can be used to revisit chemical and physical evolution predictions for large icy bodies. The absence of sulfates at Ceres is consistent with the high partial pressure of hydrogen expected in a body of that size [28, 17]. Hence sulfates are unlikely to represent the main form of sulfur in Titan and Ganymede, contrary to assumptions in recent models [29]. More generally the fate of key anions, such as sulfur and chlorine, needs to be revisited. Chlorine-based salts have been suggested for Europa [30, 31] and are likely to also be dominant salts in other icy satellites. Models of Ceres’ frozen ocean [17] may apply to other large volatile-rich bodies that are predicted to have hosted a transient liquid layer based on thermal evolution models (e.g., Hygiea, Pallas).