ELEMENTAL CONSTRAINTS ON CERES HYDROTHERMAL EVOLUTION: REGOLITH MODELS.

T. H. Prettyman[1], J. C. Castillo-Rogez[2], M. E. Landis,[3] and N. Yamashita,[1] [1]Planetary Science Institute, Tucson, AZ (prettyman@psi.edu), [2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, [3]Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO.

Introduction: Observations of the dwarf planet Ceres from Earth and by the NASA Dawn mission reveal an ocean world with likely outer solar system origins [1]. As seen by Dawn's Visible and Infrared Mapping Spectrometer (VIR), Ceres' low albedo, global surface consists of Ca-Mg carbonates, NH_4-Mg phyllosilicates, and unidentified opaque phases [2]. The observations provide evidence for pervasive aqueous alteration at low temperature and high water-to-rock ratio within Ceres' interior [3].

Bright deposits dot the surface. The faculae contain salts, primarily Na-carbonates; although, there is evidence that Occator's Cerealia Facula is capped by hydrohalite, which suggests ongoing cryovolcanism with brines sourced from a deep crustal reservoir [4]. Geophysical data indicate a differentiated interior with a rocky mantle covered by a 40-km thick crust containing water ice and clathrate hydrates, salts, phyllosilicates, and organic matter [5-7]. A weak subcrustal layer may contain residual brines [8, 9]. Brines may also form in shallow, transient hydrothermal systems induced by impact heating [8, 10].

Aliphatic organic compounds were detected by VIR in and around Ernutet crater [e.g., 11]. Telescopic UV observations suggest organic matter degraded by exposure to ionizing radiation is widespread [12]. Organic matter as a significant crustal component is supported by many lines of evidence, including measurements of regolith elemental composition by Dawn's Gamma Ray and Neutron Detector (GRaND), laboratory studies, joint analyses of GRaND and VIR data, and hygrometry [13-18]. The origin and fate of crustal organic matter is intimately linked to changing alteration conditions, resulting in the production of carbonates and – possibly – abiotic synthesis [19].

The objective of this work is to refine and expand the available elemental data from GRaND to further explore aspects of Ceres' hydrothermal evolution and crustal processes. Geochemical modeling is used to test hypotheses for Ceres' interior evolution against remote sensing data. In this study, models of regolith composition are compared with GRaND elemental data.

Regolith-crustal models. The available data support the formation of a subcrustal ocean that gradually froze beneath a volatile-rich outer shell. As such, the outermost crustal layer is a mixture of aqueously altered rock and solids precipitated from freezing brine with unknown contributions from the infall of exogenic material. The interaction of water
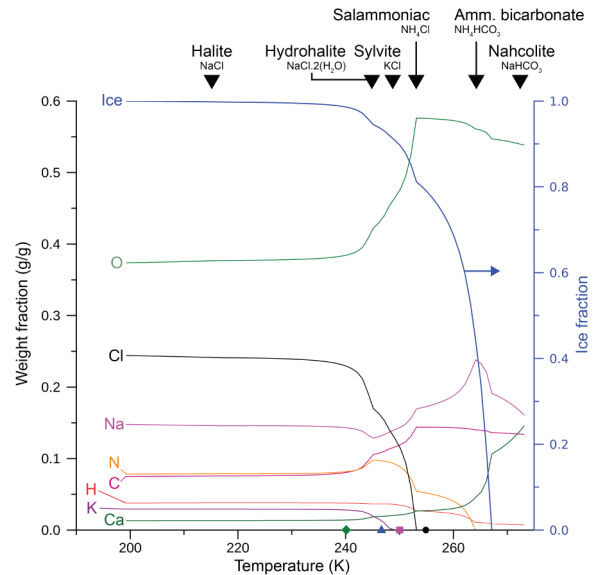

Figure 1. Elemental composition of salts precipitated from brine freezing under representative conditions within Ceres' outer crust (via FREZCHEM). Crystallization temperatures of minerals are shown along the top of the chart (▼). The fraction of ice (right axis) indicates freezing progress. The first precipitates are NH_4-Na bicarbonates, followed by halide minerals, with halite forming last. Nahcolite eventually dehydrates to form sodium carbonate, which is found on Ceres' surface. Brine temperatures in Fig. 2 are shown on the horizontal axis.
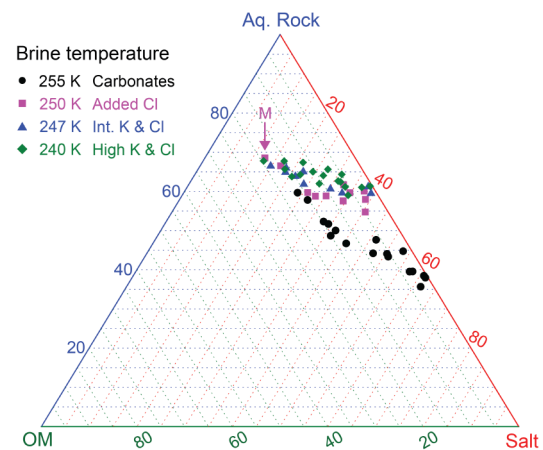

Figure 2. Randomly sampled mixtures of aqueously altered rock (Aq. Rock), salt, and organic matter (OM) that satisfy elemental constraints for [H] and [C] within Ceres' global, ice-free regolith. The mixtures include salts derived from brines at different temperatures (legend and Fig. 1). Some mixtures with chlorine-bearing solids that precipitated prior to crystallization of sylvite (squares, 250 K) can match all available elemental constraints (H, C, Cl, K, Fe): e.g., a match (M) occurs for 19% OM, 12% salt, and 69% rock.

with rock within Ceres' interior was modeled using the Geochemist's Workbench (GWB) for an assumed chondritic input composition, range of water-to-rock ratios and temperatures that could produce the hydrated mineral assemblages seen on the surface [3]. Freezing of the resulting brines was modeled using FREZCHEM. Carbonates would have precipitated first followed by chlorides, including KCl and NaCl, at lower temperatures (e.g., Fig. 1). In the example, magnesite and dolomite are also present in low concentrations.

Ceres' regolith was modeled as a ternary mixture of aqueously altered rock, salts, and organic matter. Organic matter was not treated in the geochemical modeling, which assumed accreted carbon was in the form of CO_2. Instead, organic matter was introduced as an ad hoc mixing model parameter with different H/C ratios to model carbonization by ionizing radiation. Following [16], an H/C molar ratio of 0.6 was used for models presented here.

Mixing models are compared with elemental data for Ceres' global regolith in Fig. 2. Available elements include H (1.9 ± 0.2 wt.%), Fe (16 ± 1 wt.%), K (410 ± 40 μg/g), coarse bounds on C (3.5-20 wt.%) [13, 14] as well as detection limits for Cl (< 3 wt.%, Fig. 3). The upper bound selected for C is permitted by VIR observations [16, 17]. The models plotted in Fig. 2 match constraints for H and C for mixtures containing salts precipitated from brines at selected temperatures (see Fig. 1). High temperature precipitates produce compositions with insufficient Fe, K and Cl; whereas mixtures with low-temperature precipitates, which are rich in sylvite, produce an overabundance of K and Cl. The best fits are for chlorine-bearing salts that do not contain K. This implies a narrow temperature range for the formation of salts found on the global surface. All the elemental data can be matched if abundance of organic matter is high (Fig. 2).

Conclusions and next steps. Our study shows that mixtures of endogenic materials can explain the elemental composition of Ceres' global regolith, with preliminary results consistent with high concentrations of organic C. Future work will improve GRaND analyses of H, K, and Fe, quantify C and Cl, and analyze additional elements and signatures, including Mg and Si. Thermophysical modeling will provide constraints on the stability of ice and hydrated salts needed to interpret H-layering. The analyses will be applied to the global regolith and to regional studies, including Occator crater using low altitude data acquired during Dawn's final mission phase. The mixing model will be updated to include exogenic contamination. Statistical methods will be used to compare models to data to test hypotheses for Ceres formation and crustal evolution.
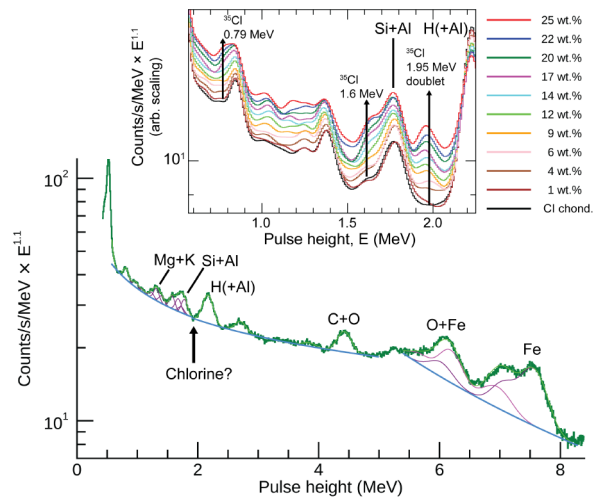

Figure 3. Detection limits for chlorine. The figure shows the analysis of a gamma-ray spectrum (green trace) accumulated at altitudes less than 100 km in the vicinity of Occator crater. Fitted components include gamma-ray peaks and continuum, with contributions from H, C, O, Mg, Al, Si, K, and Fe. The inset shows simulations of gamma ray spectra for a CI chondrite composition with added amounts of halite. Neutron capture with chlorine produces a prominent gamma ray doublet at 1.95 keV, which forms a distinct peak when chlorine concentrations are greater than several wt.%. This peak is not observed in the low altitude gamma ray spectrum. Consequently, the average concentration of chlorine in the Occator region must be less than a few wt.%.

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