PHYSICAL AND CHEMICAL CONDITIONS OF CERES' INTERIOR OVER TIME: IMPLICATIONS FOR HABITABILITY. M. Neveu[1], S. J. Desch[1], and J. C. Castillo-Rogez[2], [1]School of Earth & Space Exploration, Arizona State University, 781 E Terrace Rd, Tempe, AZ 85281, USA, mneveu@asu.edu, [2]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109.

Introduction: Our knowledge of dwarf planets has immensely improved in the past two years, with the exploration of Ceres and the Pluto system by the Dawn and New Horizons spacecrafts, respectively. Ceres (radius ≈470 km, bulk density ≈2160 kg m^{-3}, semi-major axis 2.8 AU [1]) is the water-rich world closest to the Sun. Its low surface albedo (≈0.09 [1]) yields a warm surface (180 to 240 K in the daytime [2]). This is much warmer than for any icy world in the solar system (95 to 115 K for the moons of Jupiter) and could allow for liquid water, despite low radiogenic heating and absence of tidal heating.

Indeed, Ceres' surface is blanketed by minerals resulting from the interaction of silicate rock with liquid water. Analysis of near-infrared spectra acquired by Dawn suggests that most of the surface is composed of ≈6% ammonium (NH_4)-bearing clays, 5-10% serpentine, 5-25% Mg- and/or Ca-carbonates, and 60-85% of a dark neutral absorber interpreted to be amorphous carbon or magnetite [2]. The dark surface is punctuated by bright spots of albedo ≈0.5 [1], comprising 35-40% sodium carbonate, 4-7% NH_4-bicarbonate or -chloride, 40-45% clays, and 18-24% dark material [3].

Geophysical-geochemical models: Here, we show results of 1-D models of Ceres' interior over time that couple geophysics (differentiation of coarse-grained rock from warm ice while mud fines remain suspended in melt; hydrothermal circulation of fluids through the porous rock core; parameterized convective heat transfer [4]) and geochemistry (with PHREEQC [5]).

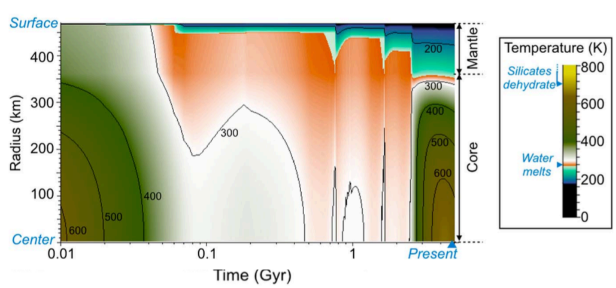

Fig. 1: Simulated temperatures inside Ceres over time.

Ceres can harbor subsurface liquid for billions of years: As shown in Fig. 1, temperatures in Ceres' hydrosphere can reach up to 250 K at the present day (allowing liquid brine pockets). With a smaller core and more mud, the mantle is warmer: around 275 K [4]. Dawn gravity and shape measurements suggest an interior structure bracketed by these cases [6]. Pressures reach up to 2000-2500 bar, similar to those of hydrothermal fields in Earth's oceans.

Chemistry of Ceres' ocean: Our simulations [7] qualitatively reproduce Ceres' surface mineralogy, assuming that chondritic material and aqueous fluids react to equilibrium (Fig. 2). Fluids (pH 9.5 to 12) are enriched in Na and oxidized and reduced C, with some reduced N. This is not only compatible with bright spot material having formed from freezing and/or dehydration of fluids exposed to space, but also suggests that liquid reservoirs on Ceres had abundant supplies of these bioessential elements, originating from chondritic organics and, perhaps, cometary ices. In contrast, S is notably depleted in the fluid, sequestered instead in rock as sulfides. P is either present as dissolved phosphate or sequestered as hydroxyapatite.

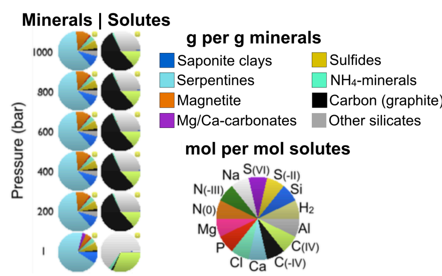

Fig. 2: Equilibrium minerals and solutes produced by CM chondrite reacting with pure water at a 1:1 mass ratio and 273 K [7].

The most common habitat? The timescale of redox energy availability is unconstrained, and hinges on that of rock alteration. It was likely short for mud fines, but redox energy could be available today if deep reduced core rock is still being exposed to oxidizing, circulating hydrothermal fluids. Thus, Ceres' balmy, nutrient-rich, muddy ocean could have offered a habitat for billions of years. Since dwarf planets in the main and Kuiper belts (where larger sizes offset colder surfaces to keep interiors warm) outnumber planets and moons in our solar system, this type of habitat may be the most common in any planetary system.

References: [1] Russell C. T. et al. (2016) *Science, 353,* 1008–1010. [2] De Sanctis M. C. et al. (2015) *Nature, 528,* 241–244. [3] De Sanctis M. C. et al. (2016) *Nature, 536,* 54–57. [4] Neveu M. and Desch S. J. (2015) *GRL, 42,* 10197–10206. [5] Parkhurst D. L. and Appelo C. A. J. (2013) *USGS Techniques & Methods, 6,* A43. [6] Park R. S. et al. (2016) *Nature, 537,* 515–517. [7] Neveu M. et al., submitted to *GCA*.