CRACKING IN CERES' CORE AS AN OPPORTUNITY FOR LATE HYDROTHERMAL ACTIVITY.

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Liquid Water Inside Ceres: The icy dwarf planet Ceres (radius ≈475 km, density 2.1 g.cm^{-3}, semi-major axis 2.8 AU) is the only body besides the Earth and Mars where carbonates have been observed along with brucite, another product of aqueous alteration [1]. Ceres will be visited by the *Dawn* spacecraft in 2015, which will offer an opportunity to constrain the origin of this large icy body. For example, it could have formed along with main-belt objects, or with Kuiper belt objects (KBOs) [2].

Models of Ceres' thermal evolution have predicted the existence of liquid water throughout most of its history [3,4], provided that it accreted one to a few percent ammonia (NH_3) acting as antifreeze with respect to water. Ammonia has been predicted to condense within the snow line [5] and observed on a few outer Solar system bodies [6,7,8]. The eutectic point of a H_2O-NH_3 mixture is around 175 K [9], much lower than that of pure water (273 K) and brines (<210 to 250 K [10]). We have applied to Ceres thermal evolution models developed for KBOs [11] with NH_3/H_2O=1% and confirmed the long-term preservation of a deep liquid layer in Ceres [12], whereas in absence of ammonia our models cannot maintain liquid. Observations and models both indicate that (a) aqueous alteration played a role in Ceres' history, and (b) Ceres' interior may have been habitable, and could still be. This brings about the need to consider geochemical processes when modeling Ceres' evolution.

How Much Hydrothermal Activity? Shape data indicate that Ceres likely differentiated into a silicate core and a water-ice mantle [3,4,12,13]. At the core-mantle boundary, water-rock interactions can occur if a thermal gradient is high enough to initiate the circulation of fluid through hot, porous rock [14]. The core porosity and depth of fracturing determine the extent of hydrothermal activity as well as the water/rock ratio (W/R), a key geochemical parameter.

Cracks develop as the core cools and contracts. At high enough pressure P and temperature T, cracks relax and seal. The balance of these two phenomena determines the depth of cracking z into the core. Previous models [14] have shown that Ceres-sized icy bodies should have a core fractured throughout ($z > R_{\text{core}} = 375$ km), assuming a constant cooling rate $\dot{T}$ of 1 K/yr, i.e., that typical of Earth's mid-Ocean ridges, and using T and P profiles with depth from static geophysical models [15]. Our geophysical *evolution* models have predicted that Ceres' core has been cooling much more slowly (a few 100 K/Gyr) from 2 Gyr until today (4.56 Gyr), following a decrease in radiogenic heating [4,12]. We predict lower $\dot{T}$ because radiogenic heat is not removed as efficiently by conduction from the low thermal conductivity rocky core as it is removed at Earth's mid-Ocean ridges through volcanism. Instead, heat builds up in the core, yielding a temperature gradient steeper than that predicted by [15].

Model Equations: Parameters and their values used in the following equations are further described in [14] and references therein. T anisotropy between square silicate grains result in a mean stress $\overline{\sigma}$ that depends on $\dot{T}$. The threshold temperature at which stress starts accumulating is T', defined such that $\overline{\sigma}(T') = 0$. An approximate analytical expression for T' is:

$$T' \approx \frac{Q}{R_G}\left[ln\left(\frac{12\Omega D_0 \delta_b E}{3^{1/2} n k_b L^3 \dot{T}}\right)\right]^{-1} \tag{1}$$

where Ω is the atomic volume, D_0 and δ_b the grain boundary diffusion coefficient and width, E Young's modulus for all grains, k_b Boltzmann's constant, $2L$ the grain size, Q the activation enthalpy, R_G the gas constant, and n is an empirical fitting parameter.

Let us consider an inclusion within a matrix. If the thermal expansion coefficient of the inclusion is higher than that of the matrix, tensile stress will develop upon cooling. Microfractures occur when the tensile stress intensity K_I exceeds a critical value, $K_{IC} = 0.6 \pm 0.3$ MPa m$^{1/2}$ for olivine. K_I is estimated from T and P:

$$K_I = (\frac{2}{\pi a})^{1/2} \int_0^a \frac{\sigma_{yy}(x, T, T') x^{1/2}}{(a-x)^{1/2}} dx - P(\pi a)^{1/2} \tag{2}$$

where a flaw of size $a < 2L$ extends from the grain boundary ($x = 0$) to $x = a$. The pressure P tends to reduce the tensile stress. $\sigma_{yy}(x, T, T')$, whose analytical expression can be found in [14], is the normal stress along the x-axis.

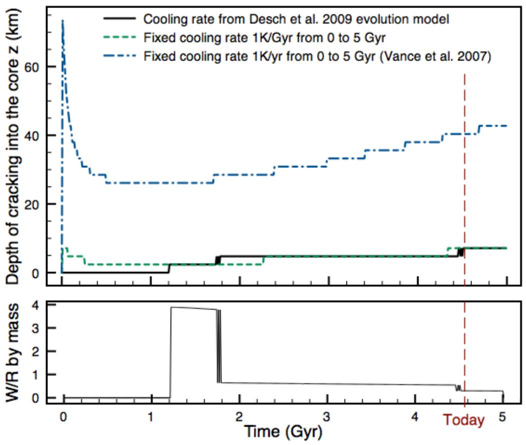

Figure 1: *Top:* Cracking depth over time for two arbitrary cooling rates suggested in [14], and for a cooling rate that changes over time according to the thermal evolution models of [11,12]. *Bottom:* W/R over time by mass, assuming all the liquid can react with all the cracked rock. The mass of cracked rock is estimated from the solid $z = f(t)$ curve above.

Depth of Cracking: With the T and P profiles inside the core generated by our thermal evolution models [11,12], we find that the upper ~40 km of the core are cracked today for a constant cooling rate $\dot{T}$ of 1 K/yr (Fig. 1). Our models suggest $\dot{T}$ ~100 K/Gyr starting at 1.2 Gyr at the core-mantle boundary (2 Gyr at the center), yielding a present z ~7 km, comparable to that obtained with a constant $\dot{T}$ ~1 K/Gyr. The sensitivity of z to $\dot{T}$ found in this study is consistent with [14].

Timescale of Hydrothermal Circulation: Where a core is cracked, we assume a permeability κ comparable to that of seafloor supporting hydrothermal circulation on Earth (10^{-12} m^2, compared to 10^{-17} m^2 far from hydrothermal regions [14]). The 1-D velocity of a fluid through porous rock is $V = F(\kappa/\mu)$, given a buoyancy force F and a dynamic viscosity μ. Heating from below drives convection through the pores if the Rayleigh number $Ra = \Delta T \rho^2 g \alpha C_P \kappa z/(\eta k)$ exceeds the critical value $Ra_c \approx 40$ [16], ΔT being the drop in T across the cracked zone, z its thickness, ρ, α, C_P, and η the density, thermal expansion coefficient, heat capacity and viscosity of the fluid, g the gravitational acceleration, and k the thermal conductivity of the rock [16]. If convection occurs, the buoyancy force has magnitude $F = 1/2 \rho g \alpha (dT/dr) l_{mix}$ over a mixing length l_{mix}. Assuming the fluid thermalizes with its surroundings (by diffusion) after flowing one mixing length, we rewrite the flow velocity in terms of l_{mix} and the dimensionless Peclet number Pe: $V = (D/l_{mix})Pe$, where $Pe \approx 1$ and D is the thermal diffusivity of the rock. With two expressions combining V and l_{mix}, we can solve for l_{mix} to find the flow velocity: $V \approx [\rho g \alpha (dT/dr) \kappa/(2\mu)]^{1/2}$. For $g = 0.3$ m s^{-2}, $\alpha = 7 \cdot 10^{-5}$K^{-1}, $dT/dr = 1$ K km^{-1}, $\kappa = 10^{-12}$ m^2, $D = 2.4 \cdot 10^{-7}$ m^2 s^{-1}, and $\mu = 2 \cdot 10^{-3}$ Pa s, we estimate $V \approx 35 Pe^{1/2}$ km Gyr^{-1}: fluid moves through the core on geological timescales. We note that precipitation of salts into the pore spaces of the rock could reduce the rock permeability and shut off hydrothermal circulation [17]: this remains to be investigated.

Conclusion: Numerical estimates suggest the upper few km of Ceres' core are cracked. Together with an analytical estimate of a few 10 km/Gyr for hydrothermal circulation, this indicates that fluid flow through the cracked layer can happen quickly enough that the whole layer experiences hydrothermal alteration. This calls for increased fidelity models coupling physics and geochemistry that account for the feedback between the evolution of the rock composition and its physical properties (e.g. thermal conductivity, porosity). Most importantly, hydrogeochemistry influences the nature and amount of antifreezes (ammonia, salts) available to preserve a deep liquid layer over the long term.

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