MODELING CORE CRACKING, A KEY FACTOR IN THE GEOPHYSICAL EVOLUTION AND HABITABILITY OF CERES.
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The Importance of Core Cracking: Cracking of the rocky core of icy bodies could represent a major stage in their evolution. The cracking depth determines the core cooling timescale, because the circulation of aqueous fluids through fractures and changes in core porosity affect heat transfer. The extent of cracking also influences the temperature T, confining pressure P_c, and water:rock ratio at which water and rock interact. The resulting chemistry determines the amount of chemical energy and nutrients available for life, and feeds back on fluid and rock properties. Therefore, core cracking needs to be properly modeled.

We present a model to (a) quantify the extent of cracking in icy body cores, and (b) infer T, P_c, and the bulk water:rock ratio at which water-rock reactions may take place. This model requires input from a thermal evolution code [1,2] that provides temperature and structure profiles inside icy bodies over time. We applied our model to Ceres (radius 475 km, density 2.1 g cm^{-3}, semi-major axis 2.8 AU), about to be visited by the *Dawn* spacecraft.

Core Cracking Model: To our knowledge, there exists only one model of core cracking on icy bodies [3], despite the importance of this phenomenon. In this model, the silicate core of an icy body contracts as it cools. Grains of different minerals contract at different rates, causing stress and cracking. Cracks heal if the temperature and pressure are high enough for rock to be ductile. Building on the model of Vance et al., we have included other processes by which cracking may occur, based on models of hydrothermal systems on Earth.

Thermal expansion mismatch. Core cracking can occur if the core heats up and expands; this is the reverse process of that studied by Vance et al. [3] (Fig. 1a). Thermal evolution models suggest that core temperatures for Ceres increase for the first ~2 Gyr after its accretion, because heating by long-lived radionuclide decay exceeds cooling by conduction. Past 2 Gyr, cooling prevails. We modeled thermal mismatch using the equations of [3].

Thermal pressurization of pore water. If a core with pore water is heated, the water expands to a higher extent than the silicate matrix (Fig. 1b). The pore pressure increase over P_c, dP_{pore}, due to a temperature increase dT is given by:

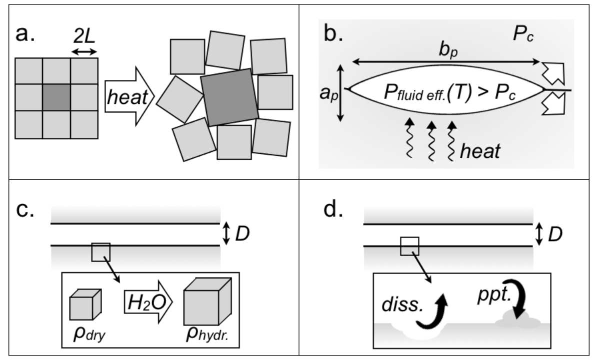

Figure 1: Cracking phenomena included in our model. *a.* Thermal expansion mismatch of mineral grains. *b.* Thermal pressurization of pore water. *c.* Swelling of rock upon hydration. *d.* Dissolution and precipitation of mineral species.

$$dP_{\mathrm{pore}} = \frac{\alpha_w(T, P_c)}{\beta_w(T, P_c)}\, dT \quad (1)$$

where α_w and β_w are the expansivity and compressibility of pure liquid water. A multiplicative term $(1 + 2\, b_p/a_p)$ accounts for the geometry of elliptical pores of minor and major axes a_p and b_p [4]. Moreover, relaxation of the rock matrix can mitigate thermal pressurization: a term $\frac{b_p}{a_p}\frac{3(1-2\nu)}{E}$ is then added to β_w, where E and ν are the rock's Young modulus and Poisson ratio [5].

Rock swelling during hydration. Incorporation of water molecules into a dry rock matrix results in swelling of the rock (Fig. 1c). The corresponding change in crack width ΔD of a 2-D crack after a time Δt can be expressed as:

$$\Delta D = -2\left[\left(\frac{\rho_{\mathrm{hydr.}}}{\rho_{\mathrm{dry}}}\right)^{-1/3} - 1\right] \times R_{\mathrm{hydr.}} \times \Delta t \quad (2)$$

where $\rho_{\mathrm{hydr.}}$ and ρ_{dry} are the densities of hydrated and dry rock, and $R_{\mathrm{hydr.}}$ is the velocity of the hydration front into a rock layer. If hydration swelling causes a crack of width D to close, residual swelling generates compression stresses σ that can open new cracks. The stress σ is given by Hooke's law, $\sigma = E\epsilon$, where $\epsilon = (\Delta D - D)/(R_{\mathrm{hydr.}}\, \Delta t)$ is the compression strain.

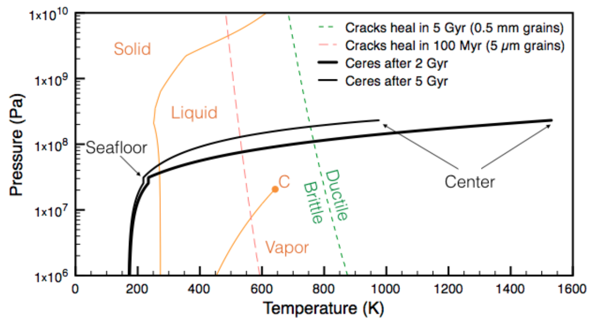

Figure 2: *Orange curves:* Phase diagram of pure water. *Black curves:* Pressure-temperature ($P-T$) profiles inside Ceres obtained using the thermal evolution model of [2]. *Dashed curves:* Brittle-ductile transition (BDT) for serpentinite in two cases. The BDT occurs near the critical temperature of water: since cracks occur in the brittle zone, we neglect supercritical processes in cracks.

Dissolution of mineral species. As fluids react with minerals, dissolution can erode cracks, whereas precipitation clogs them (Fig. 1d). The resulting change in crack width after a time Δt is given by:

$$\Delta D = \sum_{i=1}^{\text{N species}} \frac{R_i \ \rho_w \ \Delta t \ V_i(T,P)}{A/V} \qquad (3)$$

where ρ_w is the density of water, V_i is the mineral molar volume, $A/V = 2/D$ is the crack area-to-volume ratio, and R_i is the rate of dissolution:

$$R_i = (A/V) \ k_{i \text{ diss.}} \left(1 - \frac{Q_i}{K_i(T,P)}\right) \qquad (4)$$

with $k_{i \text{ diss.}}$ an experimental rate constant, and Q_i and K_i the activity product and equilibrium constant of the dissolution reaction [6]. A negative rate indicates precipitation. We consider only three species for simplicity: aqueous silica, carbonate, and chrysotile serpentine.

Brittle-ductile transition in hydrated rock. The rock strength at which rock yields to stresses is the lower of its brittle and ductile strengths. We adopt brittle strength parameters for serpentinite (coefficient of friction, frictional cohesive strength) from [7], and ductile flow parameters (grain size exponent, diffusion creep activation energy and volume) from [8]. We do not allow cracks to persist in the ductile regime past a time (strain rate)$^{-1}$.

Other phenomena: Thermal expansion of the rock matrix, fluid pressure changes linked to conduit size, elastic relaxation of cracks, anisotropy in rock properties, species transport, and, most importantly, supercritical processes [9] were not included. Fig. 2 shows that supercritical processes may not matter much for Ceres, because the $P_c - T$ conditions at which rock is brittle are in the subcritical liquid region of the water phase diagram.

Depth of Cracking: With nominal parameter values, cracks occur everywhere in Ceres' core. The main cracking process is pore thermal pressurization, which fractures the lower 80-90% of the core that are most strongly heated. The upper 5-20% of the core are cracked from grain expansion mismatch, stronger at lower P_c. The former process does not occur past 2 Gyr, once Ceres' core ceases heating [1]. Subsequent crack persistence depends on the crack healing timescale, which itself is sensitive to the mineral grain size d. For $d = 0.5$ mm, cracks remain open on Gyr timescales in the upper 50% of the core (100-200 km; Fig. 2). However, cracks heal faster for smaller d. If $d \sim 5\mu$m [10], only the upper 50-100 km of the core remain cracked after 100 Myr. These results do not account for species dissolution and precipitation, which happen on much smaller timescales.

Water:rock ratio: Our thermal evolution models predict that a liquid layer 5 km deep in contact with the core could persist to the present day, provided Ceres accreted 1% ammonia antifreeze with respect to water. If all the liquid can interact with all the cracked rock, the resulting bulk water:rock ratio is of order 0.01 by mass. Thus, very little water may have reacted with rock. However, this ratio may be higher if more ice is melted, a possible outcome if hydrothermal circulation leads to enhanced heat transfer from the core into the ice shell. We plan to investigate this by fully coupling our thermal evolution and cracking codes.

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