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Cracking in Ceres' core as an opportunity for late hydrothermal activity

Marc Neveu[1*], Steven J. Desch[1], Julie C. Castillo-Rogez[2]

1. School of Earth & Space Exploration, Arizona State University, Tempe, AZ, USA.
2. Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA

*mneveu@asu.edu

ASU Astrobiology

ASU School of Earth & Space Exploration — Arizona State University

Keck Institute for Space Studies — JPL Jet Propulsion Laboratory — NASA

1. Liquid water inside Ceres!

Ceres (radius ≈475 km, density 2.1 g•cm^{-3}, semi-major axis 2.8 AU) bears aqueously altered minerals on its surface [1].

Its density suggests that it is made of ice and rock. Fig.1 shows its probable internal structure. (Not to scale.)

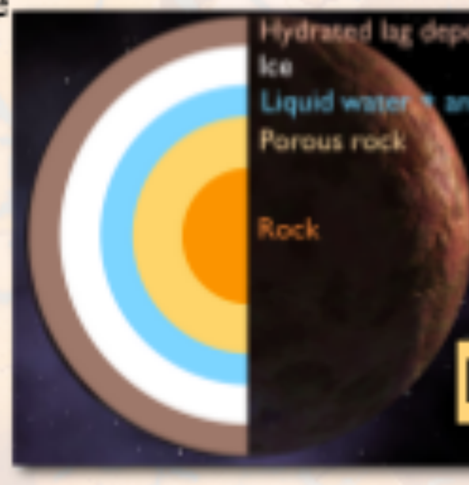


Fig.1

Models of Ceres' thermal evolution [2] predict that it had liquid water throughout its history, provided it also had **antifreezes.**

E.g., **ammonia** (NH_3) can depress the freezing point to 176 K, close to Ceres' surface temperature, 165 to 200 K.

Observations and models thus both indicate that water-rock interactions, likely hydrothermal, shaped Ceres' evolution.

2. How much hydrothermal activity?

Fig.2 shows the evolution of the temperature inside Ceres, modeled using the code of Desch et al. (2009) [3]. Heating by radioactive decay melts ice and drives differentiation, providing an early opportunity for hydrothermal activity.

Past 2 Gyr, Ceres cools. Cracks in the rock develop upon contraction of its cooling core. **Here, we model the formation of such cracks.** Liquid convection initiated through core cracks drives **late hydrothermal activity**.

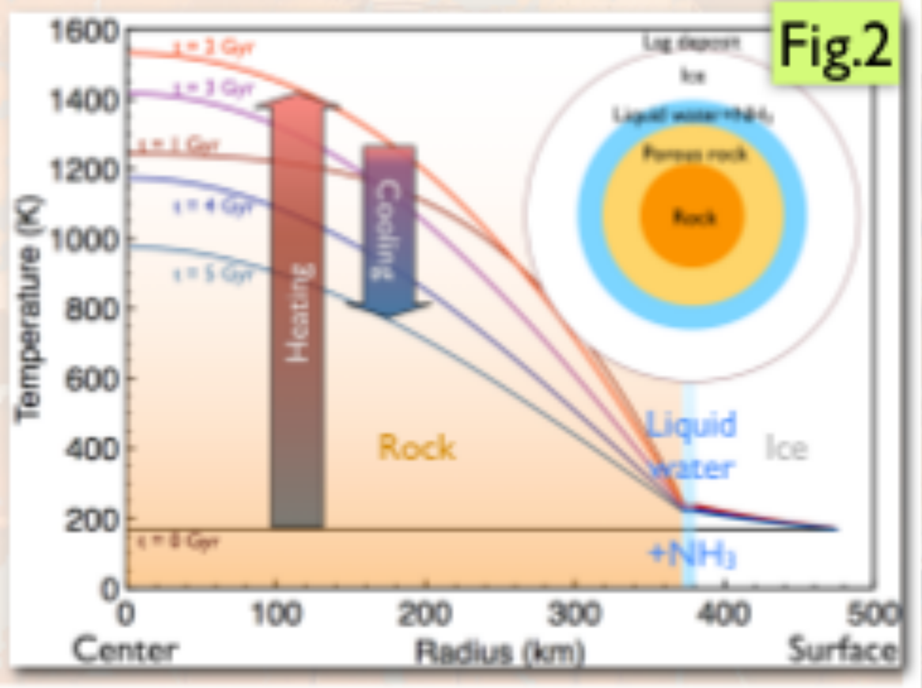


Fig.2

Ceres' radius, distance, density

Thermal evolution model, 1-D (Desch et al. 2009)

T(r,t) P(r,t) composition (r,t)

Cooling rate ∂T/∂t (r,t)

Cracking model (Vance et al. 2007)

Stress intensity $K_I(r,t) > K_{I\,cr.}$?

Result: depth of cracking z

3. Modeling crack formation

Tracks the temperature T(r,t) inside Ceres:

$$\frac{\partial E}{\partial t} = \nabla \cdot \left(k(T, Ra) \frac{\partial T}{\partial r} \right) + \Sigma S_{\mathrm{rad}} e^{-\lambda t}$$

heating/cooling = balance of conductive fluxes (in-out) If convection, set a high k. + Sum of the radionuclide heating rates

$E \rightarrow T$ using an equation of state for either rock or water-ammonia, using heat capacities and latent heats.

From T(r,t), tracks composition and pressure P.

When rock cools in Ceres' core, mineral grains shrink [4]. By how much? It depends on their thermal expansivity, α.

Stresses occur between grains of different α, increasing with cooling rate and Δα:

$$\sigma_{yy}(x) = \frac{E \cdot \Delta\alpha \cdot (T' - T)}{2\pi(1-\nu^2)} \cdot (\text{crack geom. in } x)$$

$$T' \propto \left[ln \left(\propto \frac{1}{\frac{\partial T}{\partial t}} \right) \right]^{-1}$$

is the temperature at zero stress, often higher than T by a few 100 K.

Can those stresses lead to cracks? Yes, if the stress intensity K_I (a stress•$x^{1/2}$) exceeds a critical value, $K_{I\,cr.}$ = 0.6±0.3 Pa•m$^{1/2}$ for olivine [4] or hydrated rock [5] at 1 bar ($K_{I\,cr.}$ ↗ with P).

$$K_I = \left(\frac{2}{\pi a}\right)^{1/2} \int_0^a \frac{\sigma_{yy}(x) \cdot x^{1/2}}{(a-x)^{1/2}} dx - P \cdot (\pi a)^{1/2}$$

Notice that a high T and/or P, reached at depth z, will prevent cracks from forming.

The **depth of cracking z** determines the space available for water and rock to interact.

4. Results: depth of hydrothermal layer

Fig. 3:
A high cooling rate comparable to that at Earth's mid-ocean ridges (1K/yr) yields a core cracked down to 30-40 km, ±50%. The core's radius is ≈350 km.

Here, the cooling rate is fixed arbitrarily, so the depth of cracking over time is determined by the temperature T. T is highest (and z smallest) between 1 and 2 Gyr (see Fig.2)

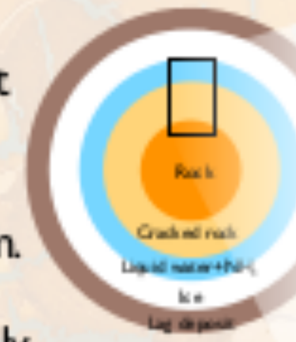


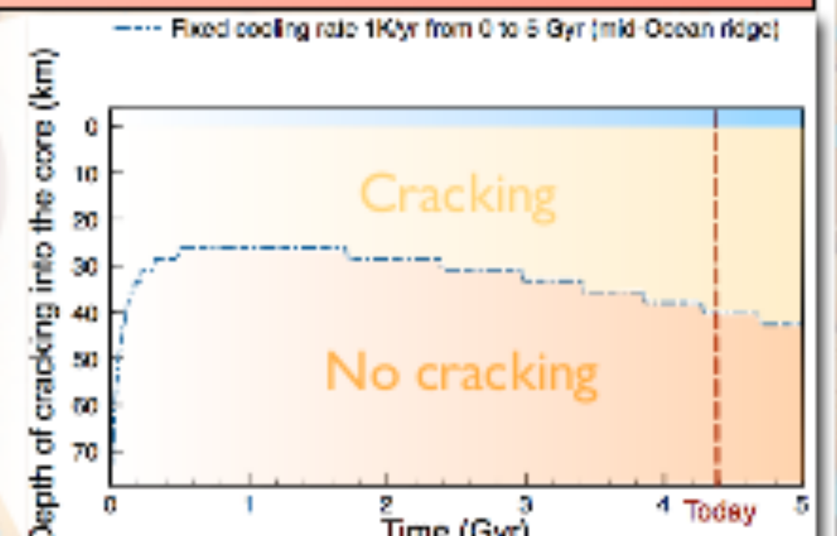
Fig. 3


Fig. 4:
Same plot for a much lower cooling rate, 1 K per billion year. Less cooling leads to less cracking: z≈5-10 km.

z is still smallest between 1 and 2 Gyr.

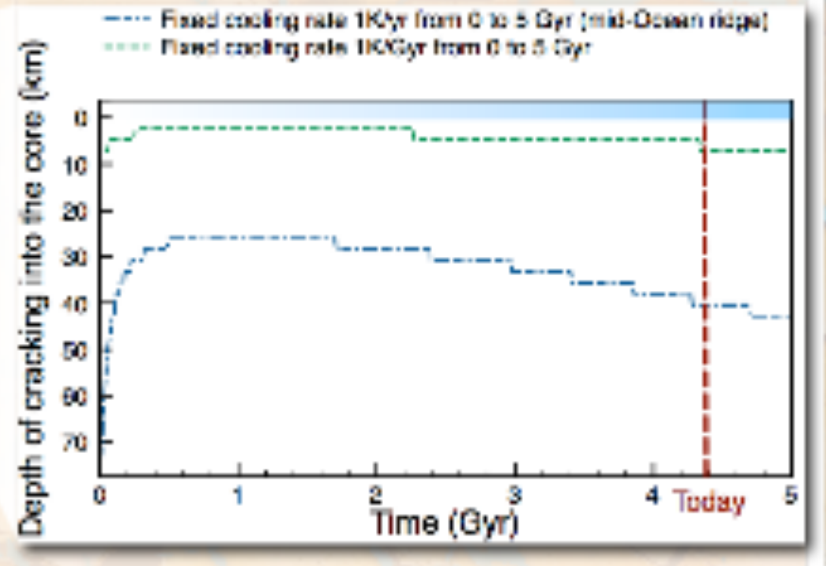
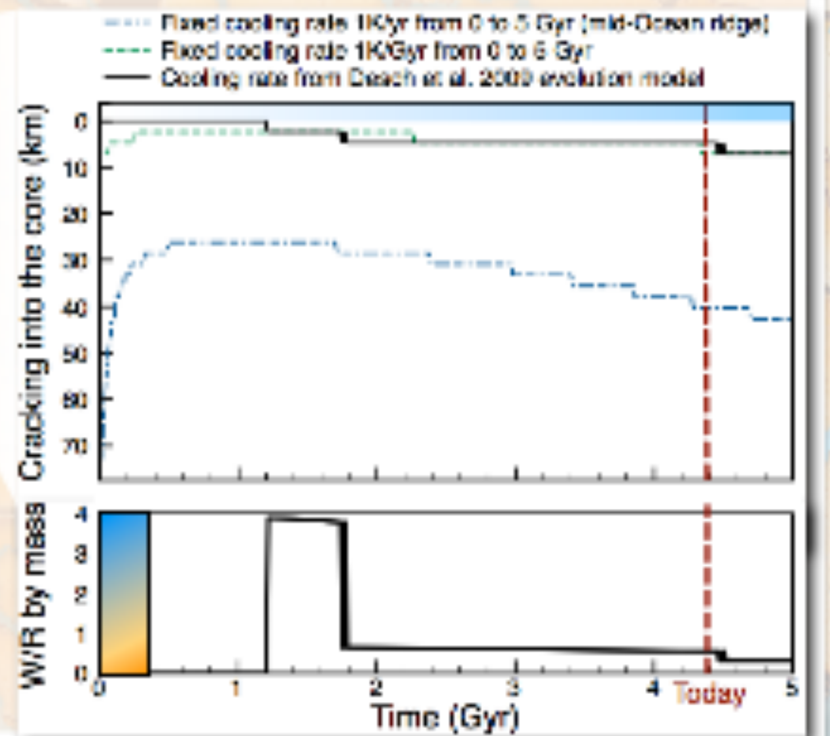

Fig. 4


Fig. 5:
Now using a "realistic" cooling rate, calculated from the thermal model output. No cracks develop until the core starts cooling between 1 and 2 Gyr, by a few 100 K per billion years. **The present depth of cracking is z≈5-10 km.**

The **water/rock ratio**, a key geochemical input, is calculated as the ratio [total mass of liquid / total mass of cracked rock]. It **decreases over time**, because cooling leads to liquid freezing and crack formation.


Fig. 5


Take-home message:

1. Water-rock interactions likely played a major role in Ceres' evolution.
2. We have introduced the first time-dependent core cracking model for an icy body. We found that late hydrothermal circulation should have been superficial.
3. This provides context for measurements by *Dawn* at Ceres in 2015.

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References: [1] Rivkin et al. 2011. *Space Sci. Rev.* 163, 95-116. [2] Castillo-Rogez and McCord 2010. *Icarus* 205, 443-459. [3] Desch et al. 2009. *Icarus* 202, 694-714. [4] Vance et al. 2007. *Astrobiology* 7, 987-1005. [5] Funatsu et al. 2004. *Int. J. Rock Mech. & Mining Sci.* 41, 927-938.