Paper Number: 2721

Differentiation models of Ceres: Delayed water separation and thick crust

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Introduction: In the early phase of Ceres' formation, heat production by ^{26}Al led to large regions with a high fraction of liquid water. Water-rock differentiation is a major factor in discriminating between models of the present-day state of Ceres. We calculate differentiation models of Ceres and examine how the accretion and compaction influence formation of an ancient ocean, how water separation and convection influence the thermal evolution, and expand on the liquids in the interior and the possibility of cryovolcanism today.

Model: The model[1] includes latent heat of ice melting, water-rock separation, and convection in an ocean. The rock-fraction is 75 vol-% (phyllosilicates and salts), the ice fraction is 25 vol-%. Creep of the ice-rock matrix is crucial for differentiation. Since the asteroid accretes porous, the first deformation process is closure of the porosity φ (modeled using creep laws). Further compaction of the rock matrix leads to the percolation of water. The latter is assumed to be quasi-instantaneous: If within a radius r with φ=0 ice melts, the rock is redistributed to form a core while water forms a layer above the core and below an undifferentiated porous layer. To model convection in the ocean, the thermal conductivity is increased by a factor of 10. Material properties vary with respect to the mineralogy and porosity.

Results: Accretion scenarios considered cover cases in which Ceres competes its formation within 1.75-10 Ma rel. to CAIs. At the center, compaction starts with ice and perchlorates (φ reduced to 35% at $T\approx$180-240 K) and proceeds with annite ($\varphi\approx$21%, T≈240-270 K), antigorite ($\varphi\approx$9%, $T\approx$480-710 K), and pyrrhotite at $T\approx$700-730 K. Shallow layers remain too cold to close the dust pores. If differentiation is neglected, final temperatures are high and allow for liquid water at the depth of 13 km (Fig. 1). For 25vol-% ice, water-rock separation proceeds by water percolation in a rock matrix. Differentiation timing depends on the matrix deformation and no differentiation occurs in porous layers. However, liquid water can be present there, enabling hydrothermal convection in the porous rock. While the radionuclides are concentrated in the core, no heat is produced in the ocean. If convection in the ocean is neglected, the ocean is heated by the core and cooled through the crust. In such a case, it remains liquid until the present day. Below a depth of 12 km liquid water is present in the crust (Fig. 1). Considering convection reduces the temperature in the ocean and results in a colder present-day crust. In this case, only a basal part of the ocean remains liquid, while the upper part freezes. Liquid water is available at a depth of 116 km (Fig. 1). Compaction is an extended process that takes several hundred million years. The differentiation is extended according to this time scale even though liquid water is produced early. While the present-day depth for liquid water is sensitive with respect to the complexity of the models, the depth for various brines is varies between 1.5 and

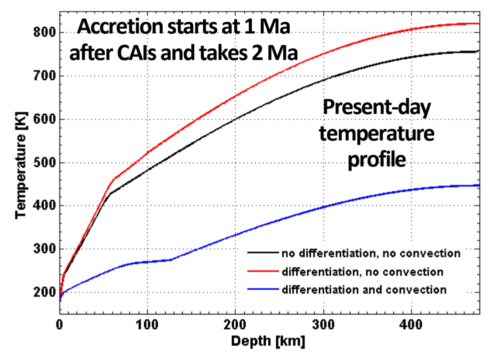

Figure 1: *Present-day temperature profiles for accretion within 3 Ma rel. to CAIs.*

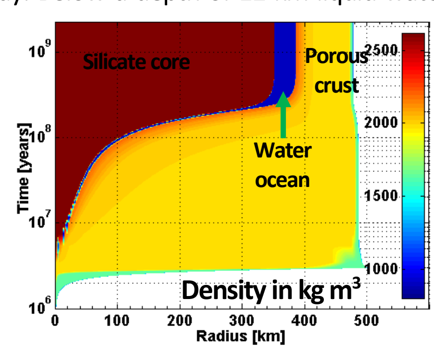

Figure 2: *Evolution of the density for accretion within 3 Ma rel. to CAIs.*

5 km for the differentiation scenarios investigated.

Conclusions: Based on a slow matrix deformation, formation of a water ocean in our models is retarded relative to the melting of ice by *O*(0.1 Ga). Compared to models without porosity, the thermal conductivity is smaller and provides insulation. This results in higher present-day temperatures, but the differentiation is not complete and a prous layer remains at the surface (Fig. 2). The Dawn mission observed surface features that are possibly of cryovolcanic origin[2,3]. Present-day temperatures calculated indicate that hydrated salts can be mobile starting at a depth of 1.5-5 km below the surface explaining the buoyancy of ice and salt-enriched crustal reservoirs. The impacts Haulani, Ikapati and Occator may have cut into these reservoirs triggering the mobility that formed cryovolcanic features.

References: [1] Neumann W et al. (2015) A&A 584: A117 [2] Jaumann R et al. (2016) LPSC XLVII [3] Krohn K et al. (2016) LPSC XLVII.