DIFFERENTIATION OF CERES AND HER PRESENT-DAY THERMAL STATE. W. Neumann and D. Breuer and T. Spohn, Deutsches Zentrum für Luft- und Raumfahrt (DLR), Institut für Planetenforschung, Rutherfordstr. 2, 12489 Berlin, Deutschland (wladimir.neumann@dlr.de).

Introduction: Ceres began its existence in an environment characterized by energetic accretion of dust and ice particles. In the early phase of its formation, primitive compositional heterogeneity of the interior was formed and the initial conditions that put Ceres on its individual evolutionary path were set by processes associated with the melting of ice. Large areas with a high fraction of liquid water must have formed leading possibly to the emergence of a water ocean and influencing thereby present-day surficial and internal characteristics. Water-rock differentiation of Ceres is, therefore, of critical importance for its evolution and potentially a major factor in discriminating between models of the present-day state to the dwarf planet.

We calculate models for the thermal evolution, compaction, and water-rock differentiation of an accreting Ceres-like asteroid. We examine how the interplay of accretion and compaction influence water percolation and ocean formation. We investigate how water separation and convection in the ocean influence present-day temperatures in the sub-surface and draw conclusions about the presence of liquids in the interior and the possibility of cryovolcanism today.

Model: The numerical model from [1] was extended to include the latent heat of melting of water ice, water-rock differentiation, and convection in a water ocean. The rock-fraction of 75 vol-% (89.5 wt-%) was assumed to include phyllosilicates and salts (annite, perchlorates, antigorite, pyrrhotite). The ice volume fraction was assumed to be 25 % (a mass fraction of 10.5 %). Creep laws for this mineralogy were implemented in the compaction subroutine. The strain rate was calculated as a volume fraction weighted arithmetic mean of the strain rates of the minerals included. The ability of the mixed ice-rock matrix to creep is crucial for differentiation. Since building material accretes as a porous aggregate, the first matrix deformation process is closure of this porosity. Only if it is reduced totally, can further compaction of the rock matrix that contains liquid water lead to the percolation of water that is squeezed out of the matrix. Thus, we treat the differentiation as a quasi-instantaneous process that occurs only in the areas where the porosity is equal to zero and liquid water is present. The model calculation proceeds as follows. On a moving frame of reference equations for the energy balance and strain rates (i.e., compaction) are solved. Upon reaching the melting temperature of ice, latent heat is consumed. If in a spherical volume with certain radius r porosity is equal to zero and the temperature exceeds the melting temperature of water ice, material is redistributed in this volume. The rock fraction forms a core with a radius that corresponds to the volume fraction of rock while water forms a layer above the core. In the water ocean, turbulent convection is simulated by increasing the thermal conductivity by one order of magnitude if the heat flux out of the ocean allows convection. No volume changes of the phases are considered since the densities of ice and water are assumed constant. Parameters (k, ρ, and c_p) correspond to the mineralogical composition and porosity and are adjusted in the differentiated core and ocean. Both short- and long-lived radiogenic nuclides are used as heat sources. Accretion starts with a km-size seed at t_0 and proceeds until t_0+t_{ac}, resulting in a final radius of ≈ 500 km which is reduced further by compaction to the present-day radius of ≈ 470 km. The initial and surface temperature is 180 K, the initial porosity is ≈ 50 %.

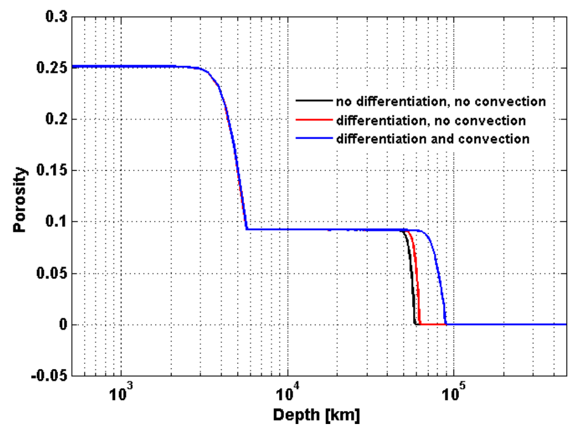

Fig. 1: Present-day porosity profiles for t_0=1 Ma and t_{ac}=2 Ma.

Results: Accretion scenarios with t_0=1 Ma and t_{ac}=1-9 Ma and an exponential accretion law were considered. Exponential accretion implies that the majority of the mass and volume accretes between $t_0+0.75t_{ac}$ and t_0+t_{ac}. Thus, combinations of t_0 and t_{ac} utilized cover cases in which Ceres competes its formation between 1.75and 10 Ma rel. to CAIs.

During the accretion, compaction at the center of the asteroid proceeds as follows. Ice and perchlorates are weaker than the three other phases and compacts fast reducing the local porosity to 35 % at T ≈ 180-240 K. Subsequently, creep of annite reduces the porosity to 21 % at T ≈ 240-270 K. After some stagnation, creep of antigorite brings the local porosity to 9 % at T

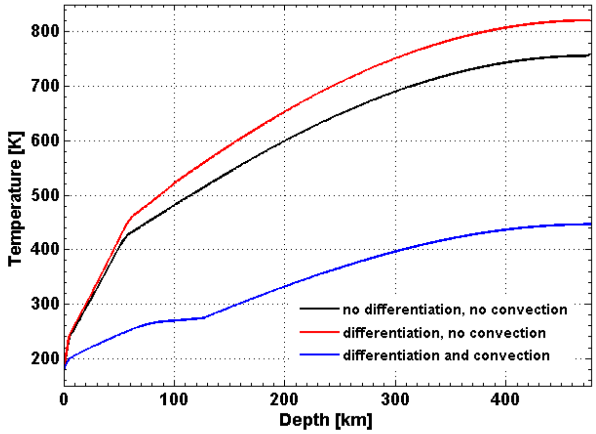

Fig. 2: Present-day temperature profiles for t_0=1 Ma and t_{ac}=2 Ma.

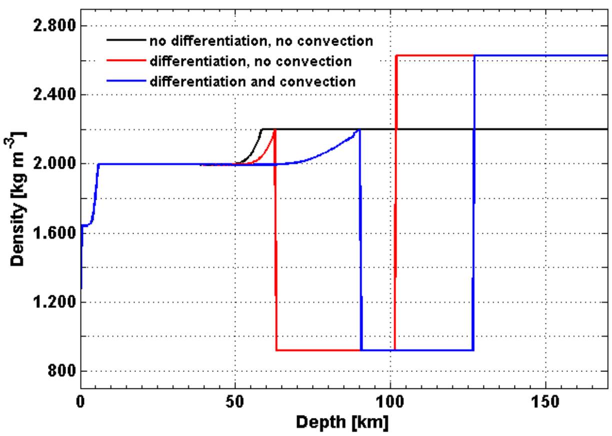

Fig. 3: Present-day density distribution for t_0=1 Ma and t_{ac}=2 Ma.

≈ 480-710 K. The strongest phase is pyrrhotite, which compacts last at T ≈ 700-730 K. The temperature at shallow depth is not high enough to close the dust pores completely (see Fig. 1).

If no differentiation is included final temperatures are rather high and allow for liquid water at the depth of 13 km (hydrothermal convection should reduce the temperature somewhat, though). Fig. 2, black line, shows the resulting present-day temperature profile.

Since the global volume fraction of ice is relatively low, water-rock separation should proceed by water percolation in a rock matrix. The timing of the differentiation depends on the ability of the matrix to deform and no differentiation is expected in porous layers. However, liquid water can be present there for a quite long time, enabling hydrothermal convection in the porous rock.

If a core and an ocean form, radionuclides are concentrated in the core. The heat production in the ocean is zero, and that in the partially porous crust is unchanged. If no convection is considered, the ocean is heated by the core and is cooled by conduction through the crust. In such a case, it remains liquid until the present day. Final temperatures allow for liquid water in the crust as well, starting at a depth of 12 km (Fig. 2, red line). Convection is an additional mechanism that reduces the temperature in the ocean and keeps the crust cold. In this case, only a basal part of the ocean remains liquid (assuming no antifreeze), while the upper part is frozen. Liquid water is available at a depth of 116 km (Fig. 2, blue line).

For the accretion scenario and mineralogical composition adopted, compaction is an extended process which takes approximately several hundred million years. The differentiation of a water ocean is extended according to this time scale even though liquid water is available early in the evolution of Ceres.

While the present-day minimum depth for the liquid water is very sensitive with respect to the degree of complexity of the models, the depth for various brines (the latter can exist already at temperatures as low as 200 K) is subject to a much smaller variation between 1.5 and 5 km for the differentiation scenarios described above.

Conclusions: In the models that assume compacted material, water-rock differentiation is quasi-instantaneous as soon as ice melts from inside out of Ceres. This takes place at the center already during the accretion, but nearly complete differentiation of Ceres is expected only after the accretion is finished. Based on a slow matrix deformation, formation of a water ocean is retarded relative to the melting of ice by O(100 Ma). Compared to the models that assume compacted material, porosity scales the thermal conductivity and acts, thus, as an insulating property. Models with a porous blanket result, in general, in higher present-day temperatures and the differentiation is not complete (Fig. 3).

The Dawn mission observed smooth plains and flow-like surface features as well as mountainous material on Ceres that are significantly younger than their surroundings and are possibly of cryovolcanic origin[2,3]. Our modeling indicates that hydrated salts can be warm enough to be mobile starting at a depth of 1.5-5 km below Ceres surface. This would explain the buoyancy of ice and salt-enriched crustal reservoirs. The impacts Haulani, Ikapati and Occator may have cut into layers of 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*.