DIFFERENTIATION OF ENCELADUS AND RETENTION OF A POROUS CORE. W. O. Neumann¹ and A. Kruse^{1,2}, ¹German Aerospace Center, Institute of Planetary Research, Berlin, Germany (wladimir.neumann@dlr.de, neumannw@mathematik.hu-berlin.de), ²Technical University of Braunschweig, Institute for Geophysics and Extraterrestrial Physics, Braunschweig, Germany.

Introduction: The Cassini mission revealed gas plumes associated with surface features called “tiger stripes” at the south pole of Saturn’s moon Enceladus. The composition of plume particles and local cryovolcanism suggested as a possible cause for the activity are typically considered in the context of hydrothermal circulation in the rocky core within a differentiated core-ocean-ice crust structure. We model the internal evolution and differentiation of Enceladus heated by radioactive nuclides and tidal dissipation. Calculating the core formation, we investigate its compaction by modeling the evolution of porosity, thereby varying the rock rheology based on different assumptions on the composition, such as grain size, creep activation energy, degree of hydration, and oxygen fugacity. We obtained “successful” final structures with a core radius of 185-205 km, a porous core layer of 4-70 km, an ocean of ≈ 10 -27 km, and an ice crust layer of ≈ 30 -40 km, that are largely consistent with the current estimates for Enceladus. By fitting the model results to these observations, we determined an accretion time of 1.3-2.3 Ma after Ca-Al-rich inclusions for Enceladus. Our models produce a porous outer core for wet and dry olivine rock rheologies supporting the hypothesis of hydrothermal circulation of oceanic water in the core. No porosity is retained for an antigorite rheology, implying that the core of Enceladus is not dominated by this mineral.

Model: For model calculations we adapted a 1D thermal evolution code used previously for Ceres^[1] to Enceladus. The updated model^[2] calculates heating by the short- and long-lived radioactive isotopes, latent heat, compaction of initially porous rock, continuous water-rock separation, redistribution of radionuclides, tidal heating, and convection in the water ocean.

A crucial aspect of the model is the calculation of the melt porosity in the rocky core during its formation and subsequent evolution (i.e., the change of the pore space filled with water). The core forms by the redistribution of water and silicate rock particles in a two-phase system after melting of ice. The melting front proceeds from the center upward. The rock particles in the H₂O-rich layer below the melting front settle and form an agglomerate with water-filled pores, while atop that a water layer forms. This agglomerate is a high-porosity core that grows along with the water layer while the melting front moves further upward. Deformation of the core can lead to a reduction of the

pores. The water displaced from them moves to the top of the core and supplies the water layer, while the rock is displaced downward according to the evolution of the porosity, and the core shrinks slightly. With time it can undergo further deformation (i.e., compaction) that is facilitated by creep processes on a geologic timescale and can be modeled considering the evolution of the porosity. The latter can be calculated from the change of the strain rate according to a creep law appropriate for the composition considered.

An ordinary chondritic composition is dominated by olivine, one of the most common rock-forming minerals likely present on Enceladus. To model compaction of a core that is dominated by olivine, we use the creep law from [3] that can describe diffusion creep of both “dry” (models A1-A4) and “wet” (models B1-B4) olivine for different values of water fugacity. Accretion of carbonaceous chondritic material rich in phyllosilicates that formed at aqueous conditions could have occurred during the formation of Enceladus. Even if only dry material, e.g., olivine, accreted, hydrothermalism could have aqueously altered this material prior or after the differentiation. For a phyllosilicate-rich composition (models C1-C2) supported by plume and E-ring spectral analyses^[4], we use the creep law from [5].

Results: Figure 1 shows the evolution of the rocky core, liquid water layer (i.e., ocean), and ice crust over a time span of 4,5 Ga for the model A2 (accretion time of 1,7 Ma after CAIs) that is representative for all successful calculations with the dry olivine rheology. The evolution starts 1,7 Ma after CAIs with an early heating by short-lived radionuclides. A strong temperature increase leads to the onset of melting, such that the melting front moves from the center toward the surface. The ocean formation starts at ≈ 3 Ma, with a significant differentiation phase from ≈ 4 Ma resulting in the formation of an ocean atop a core, finalized by ≈ 5 Ma after CAIs. During this process, compacting porous proto-core squeezes a part of the interstitial water that ascends through the porous rock into the water layer. The radionuclides are concentrated in the central part of the moon, bringing the central temperature to ≈ 800 K.

The initial porosity in the homogeneous ice-rock mixture decreases at ≈ 2.6 Ma after CAIs throughout the deeper interior at ≈ 450 K. The displaced water forms an ocean atop of the core. After ≈ 4 Ma after

CAIs the water amount in the central core part decreases to 0%. This defines a compact core region upon which a few km thick layer with a positive fraction of interstitial water forms that defines a porous outer core. It is retained because the compaction is not efficient enough to close the pores completely.

Figure 1: Evolution of the core (dark blue), ocean (yellow), and crust (light blue) shown through the evolution of the heat capacity, since this parameter has considerably different values for all structural layers, allowing, in particular, to show the evolution of the ocean and of the ice layer separately.

Although a liquid layer is retained until present, gradually extinguishing radionuclides cannot prevent a progressing solidification of the ocean on a global timescale. Additional models (A1-A4, B1-B4, C1-C2) confirm that Enceladus could be far off from a state with a solidified ice layer, since a global liquid ocean at present is obtained for a variety of parameters. A very slowly solidifying ocean shows that, assuming constant orbital conditions, a period of time longer than the age of the solar system must pass until a complete solidification can occur.

Figure 2: Final profiles of the water fraction in the upper 130 km for models A1-A4 (dry olivine), B1-B4 (wet olivine), and C1-C2 (antigorite). Note that subduction, or loss due to impacts of a top thin undifferentiated layer, is not modeled.

Figure 2 shows the water fraction profiles at 4,5 Ga (i.e., at present) in the upper 130 km of Enceladus. Although parameter values differ within each panel, they lead to models with similar final structures where only the thicknesses of the layers vary slightly. Thereby, a porous outer core is obtained only for wet and dry olivine cores while for an antigorite rheology no porosity is retained in the core, implying that the core of Enceladus is not dominated by this mineral.

Conclusions: We modeled the differentiation of Enceladus into a rocky core and a water ocean in which the core is initially porous and evolves due to compaction, and demonstrated the importance of the rheology for the final core structure. For both dry and wet olivine core, it is possible to obtain a model that satisfies conditions for a successful one, in particular, a porous outer core. Compared with different concepts of the core structure of Enceladus discussed in the literature, in particular in the framework of only a few published differentiation models^[6-9], the structure obtained resembles the core derived by [7-9] that is a non-rubble-pile solid but porous.

A porous outer core layer obtained for both olivine rheologies supports the hypothesis of hydrothermal circulation of oceanic water. Differing from an “extreme” sandpile-like unconsolidated core assumed by [10], a fully consolidated inner core and partially consolidated outer core would result in less tidal heating relative to that calculated by [10]. The less extreme assumption of a rubble-pile core made by [11] is inherently closer to our results. However, our calculations show that at least a rubble-pile inner part would be impermanent and a fast consolidation is the ultimate outcome if the core is heated to ≈ 700 K.

A porous core layer can generate additional tidal heating^[10,11] since the core mechanics would be influenced by ice or water. However, this excess heating of the core could catalyze its consolidation, reducing, in turn, the influence of this mechanism. Our results indicate that the amount of heat generated in an unconsolidated core^[10] is an overestimate. The anticipated reduction of the tidal heat generation and of the heat flux calculated in the sandpile model should be quantified in future studies.

From successful models that fit the observations and the current understanding of Enceladus’ structure, we constrain the accretion time to 1.3-2.3 Ma. The remaining free parameters (creep activation energy, grain size, etc.) cannot be constrained further, as for every extreme value it is possible to find a successful (though not favored) model by adjusting other parameters accordingly. As an antigorite rheology did not produce successful models with core porosity, it is rather unlikely that the outer core is dominated by this mineral, and the inner core should be dry due to the thermal conditions that facilitate dehydration.

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