

THE THERMAL STATE OF EARTH AFTER THE MOON-FORMING IMPACT EVENT USING NUMERICAL SIMULATIONS. N. Güldemeister¹, L. Manske^{1,2}, Christoph Burger³ and K. Wünnemann^{1,2}, ¹Museum für Naturkunde, Leibniz Institute for Evolution and Biodiversity Science Berlin, Germany (nicole.gueldemeister@mfn-berlin.de), ²Freie Universität Berlin, Institute for Geological Science, Germany, ³University of Vienna, Department of Astrophysics, Austria.

Introduction: Planetary collisions play an important role in the compositional and thermal evolution of the planetary system. The final stage of planet formation is characterized by collisions of large bodies. The Moon-forming impact event is thought to be Earth's last giant collision event, marking the end of the main accretion phase of the Earth. This large event (re)set the conditions for the subsequent thermochemical evolution of both bodies, Earth and Moon. Large parts of proto-earth are thought to melt as a consequence of the impact. To constrain the initial conditions of proto-Earth, to investigate the subsequent thermochemical evolution after the impact of a Mars-size object, and to quantify the volume of melt production, we carried out numerical simulations in 2D and 3D of giant impact events on the scale of the collision scenario that eventually formed the Earth's Moon. Focus of this work is given to the thermal state of Earth after Moon-forming-like impact scenarios.

Methods: Previously, the Moon-forming giant impact has mostly been modeled with mesh-free so-called smoothed particle hydrodynamics (SPH [1, 2, 3, 4]). In contrast, we use an Eulerian shock physics code with a fixed grid in space. The two-dimensional (2D) and three-dimensional (3D) iSALE code [5,6] is used to model the giant collision of a Mars-sized object with proto-earth. iSALE accounts for multi-material and strength and it has been demonstrated in several studies to provide accurate results on shock wave propagation and melt production [e.g. 7, 8, 9]. In 2D (head-on collision) simulations we assume two different cases, (1) the impactor and proto-earth are differentiated into an iron core and dunitic mantle and (2) homogeneous materials (dunite) for both bodies (undifferentiated). Although the

latter scenario is somewhat unrealistic we use it as a reference that may have some application to collisions of planetary embryos during the main accretion phase. In both cases we neglect a thin crust. The core of the differentiated bodies is represented by the Analytical Equation of State (ANEOS, [10]) for iron and the mantle by an ANEOS for dunite. Further, we account for the lithostatic pressure inside the planet as a consequence of the gravitational field using either central or self-gravity. We take into account an initial thermal profile for the impacted body (Figure 1). In 3D we also carry out a series of oblique impacts with different impact angles (30, 45 and 60°). The 3D simulations only consider homogeneous dunitic material so far. The impact velocity for all cases was 12 km/s. In order to quantify the volume of impact-induced melt that is produced by such a large impact, we use the so-called peak-shock pressure approach that has been used in several modeling studies [11] and is described in more detail by [12]. It is based on the assumption that the shock wave-induced increase in temperature is proportional to the maximum shock pressure the material experiences. To avoid inaccuracies in the temperature field calculated by iSALE due to diffusion, massless Lagrangian tracers are used to record peak shock pressures, which are proportional to the raise of the temperature. Further, we use the well-tested 2D simulations for validation of our 3D models. For the 3D cases, we were not able to use the tracer temperature method as described above. Instead, we directly use the final temperatures to quantify the amount of melt. This method, however, accounts for plastic work but is numerically diffusive and may overestimate the melt production. We also intend to compare our iSALE results with a SPH code in terms of temperature distribution and melt production.

Results: Simulations in 2D (head-on collisions, central-gravity) show that the volume that is fully or partially molten after the impact event significantly depends on the distribution of material, if the bodies are undifferentiated or differentiated. Figure 2 shows the degree of melting, where red represents partially and orange fully molten areas of the impactor and impacted body. For the case of undifferentiated (primitive) bodies, the volume of material that is partially or completely molten is 5.3 times the projectile volume. In contrast only 1.1 of the projectile volume is molten considering differentiated bodies. It can also be seen that the impactor mantle is completely molten, the iron core of the

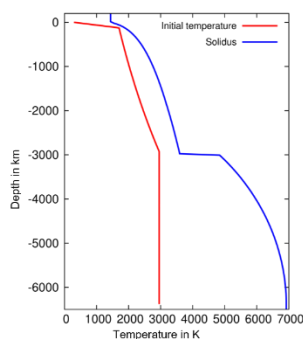


Figure 1: Initial temperature profile for the differentiated impacted body. The solidus is also shown. If the temperature exceeds the solidus, material is molten.

colliding bodies is not molten. Thus, in the case of differentiated bodies only 20 % of mantle material is molten whereas the complete mantle is molten in the case of primitive bodies. If more mantle material is molten, more decompression melting takes place (not shown here). It could be shown that melt production is significantly affected by the presence of a proto-earth core. Further, the chosen type of gravity, self or central gravity, affects the final material distribution of core and mantle of both bodies.

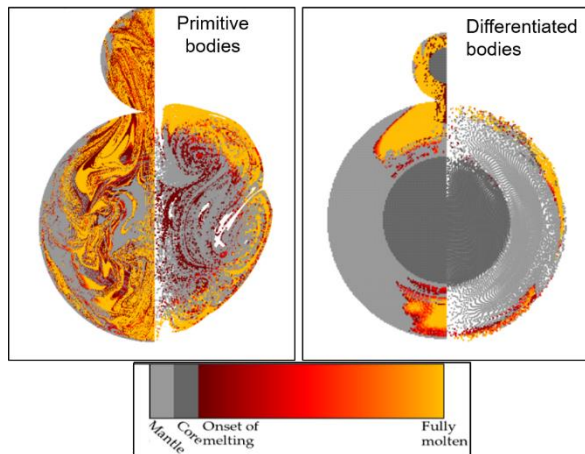


Figure 2: Melt distribution including the degree of melting after the impact of a Mars-size object with proto-earth with an impact velocity of 12 km/s considering homogeneous dunitic material (left) and differentiated bodies (right). On the left of each plot, the used tracers have been mapped back to the initial position. On the right of each plot, the final positions of the tracers are shown.

3D modelling allows for simulating oblique impacts. Figure 3 shows the melt production after the moon-forming event for oblique impacts of 30, 45 and 60 degree angle considering central-gravity, where a dunitic impactor strikes a dunitic proto-earth (undifferentiated). The simulations in 3D show a decrease of pressures and temperatures and consequently less melt production with an increase of the impact angle. The melt volume decrease from 6.5 times the projectile volume for a 60 degree angle to 5 times the projectile volume for a shallow angle of 30 degree. Thus, the degree of obliquity plays a role in terms of pressure and temperature distributions and impact-induced melt production. We note that different methods have been used to determine the amount of melt in 2D and 3D simulations. The results of the 3D cases most likely tend to overestimate the melt volume.

Discussion and Conclusion: Numerical simulations of Moon-forming-like impact events allow for quantifying the melt production as a function of impact angle, velocity, initial thermal and differentiation state.

In all our simulations giant impact events of the size of the Moon-forming impact scenario produce a global magma ocean. The melt volume decreases with impact angle and is reduced if a core is present. Only steep impact angles allow for a complete melting of the mantle. A first validation of the 3D simulations using primitive colliding bodies shows a good agreement of 2D and 3D model results with respect to temperature and pressure distribution. As different methods have been used to quantify the melt production, the volume of melt is not comparable so far.

Future work will include the implementation of a self-gravity routine in iSALE3D incorporating a Barnes and Hut approach [8] similar as in SPH codes. The upcoming simulations will mainly be carried out in 3D to consider more realistic and relevant impact scenarios of the oblique impact of a Mars-size object onto proto-earth. In addition, we will include differentiated bodies for 3D simulations, which will require further code developments. We intend to quantify melt production and to estimate the possible mixing of core material of the impactor with the mantle and core material of the proto-earth.

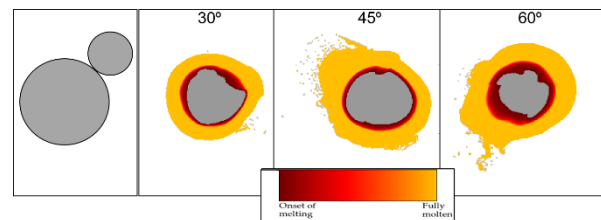


Figure 3: Melt production for oblique impacts (mars-size object impacting onto proto-earth with a velocity of 12 km/s) from a very shallow angle (30°) to steeper angles (60°). Fully molten and partially molten material is considered. The initial state is shown on the left.

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