THE THERMAL STATE OF EARTH AFTER GIANT COLLISIONS USING NUMERICAL SIMULATIONS.

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Introduction: Planetary collisions play an important role in the compositional and thermal evolution of the planetary system. The thermochemical evolution of Earth was heavily influenced by the Moon-forming event and the subsequent bombardment of the Earth Moon system by large cosmic bodies. Such impacts transfer a significant amount of energy as heat to the planet and may cause the formation of global magma oceans. Thus, large parts of proto-earth are thought to melt as a consequence of the Moon-forming impact event. The quantification of the amount of melt generated during these events is key to understand the early evolution of the Earth-Moon system. We carried out a series of numerical models using the iSALE shock physics code to investigate the generation of impact-induced melting and the distribution of melt as a consequence of giant impacts.

Our results allow for estimating whether a single giant impact event or the flux of large impactors enable the formation of a global magma ocean or whether they generate local or regional melt ponds instead.

Methods: Previously, giant impact scenarios like the Moon-forming impact event have been modeled by mesh-free so-called smoothed particle hydrodynamics (SPH [1, 2, 3]). Our models are based on an ALE (Arbitrary-Langrangian-Eulerian) code with a fixed grid in space which tend to be more accurate in modeling the thermodynamics of shock waves. We used the two-dimensional (2D) and three-dimensional (3D) iSALE code [4, 5] to model giant impacts of large objects with proto-earth.

The thermodynamic state (EoS) of the colliding bodies is calculated by ANEOS [6] for dunite, and iron representing the planetary mantle and core, respectively. Differentiated impactors are neglected at this stage, thus the impactor only consists of dunite.

We consider two different initial thermal profiles [7] for the impacted planetary body as shown in Figure 1.

We carried out a series of 2D head-on collisions, where we varied the impactor diameter and kept the impact velocity constant at 15 km/s. Additionally, we simulated oblique Moon-forming impacts and varied the impact angles (15, 30, 45 and 60°) at an impact velocity of 12 km/s.

In order to quantify the volume of impact-induced melt, we use the so-called peak-shock pressure method (‘Tracer method’) that has been used in several modeling studies before [e.g. 8, 9]. It is based on the proportionality of the maximum shock pressure and the post shock temperature increase. We compare the post-shock temperature with the solidus and liquidus [10] temperature to assess whether matter is completely or partially molten and to determine the total amount and distribution of melt.

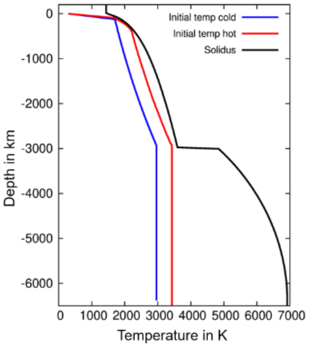

Figure 1: Thermal profile for a cold and hot Earth including a solidus function.

Results: Figure 2 illustrates the melt efficiency as a function of impactor diameter. The melt efficiency is given by the melt volume normalized by the projectile volume. The distinct increase in melt production for impactors larger than 10 km in diameter for the hot planet scenario is caused by the depth-dependence of the difference between the initial temperature and solidus (ΔT_M). The maximum in melt efficiency usually occurs at a depth that corresponds to the bottom of the lithosphere, where ΔT_M is the smallest [11] as can be seen in Figure 1.

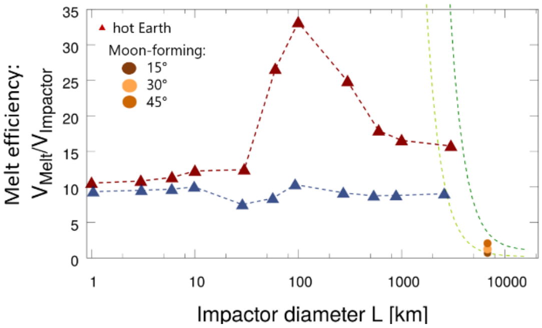

Figure 2: Melt efficiency for hot and cold Earth. Colored dashed lines indicate 100% and 20% of the normalized mantle volume ($V_{Mantle}/V_{Projectile}$). The melt efficiency for the Moon-forming impact event is also shown.

The melt efficiency in Moon-forming impact scenarios is relatively small in comparison to much smaller impacts (Figure 2). This is due to the fact, that the projectile volume is relatively big compared to the target. Our models suggest that in impact scenarios with impact angles >15° at 12km/s (~ escape velocity) a global magma ocean is formed. Figure 3 shows the degree of melting after the Moon-forming event for a cold and hot proto-Earth and different impact angles, where red represents partially and orange fully molten areas. The melt volume is about 1.2 the projectile volume for a cold proto-Earth and about 1.7 for a hot proto-Earth, which corresponds to about 20% of molten mantle material. Our simulations show that melt production decreases with decreasing impact angle. The Moon-forming impact event produces a global magma ocean although complete melting of the mantle is unlikely. The presence of the earth's core has a limiting effect on the melt production as simulations without a core have shown.

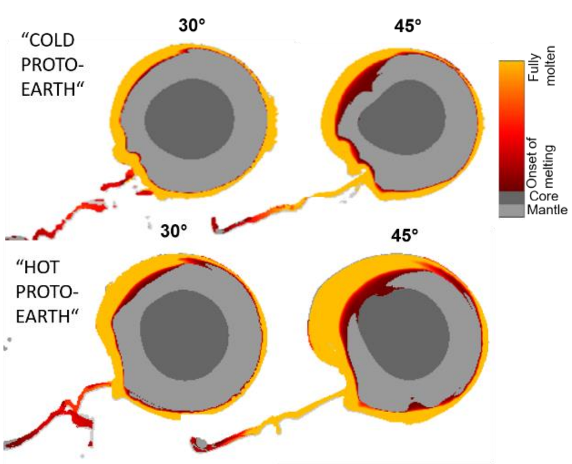

Figure 3: Cross-section of the melt distribution for a in an post-impact Earth from Moon-forming scenarios with impact angles of 30° and 45° at 12 km/s. It is shown for two different initial thermal profiles; a cold (top) and hot (bottom) proto-Earth.

Figure 4 shows the total melt production on Earth over 100 Ma intervals during the late accretion phase. The Moon-forming impact event forms a global magma ocean. The accumulated amount of melt as a consequence of the subsequent bombardment is estimated by combining a flux model [12] with the melt production as a function of impact size (Fig. 2). As we do not consider cooling and crystallization of melt over the given time-span the presented values represent upper estimates. We assume a time period right after the solidification of the magma ocean which is best represented by the hot thermal profile. Our results indicate that the bombardment during late accretion was not sufficient to re-melt large areas of the mantle causing a secondary global magma ocean. Melting of up to 5% of the mantle volume over a time period of 100 Ma is possible. Thus, the impactor flux may prolong the existence of a magma ocean but only forms regional magma ponds.

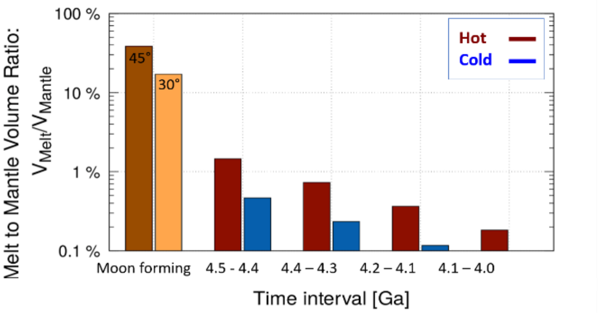

Figure 4: Cumulative melt production during different time periods on Earth.

Conclusion: **N**umerical simulations of giant collisions up to the scale of Moon-forming impact scenarios allow for quantifying the melt production as a function of impact angle, velocity and initial thermal profile. 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. Only steep impact angles allow for a complete melting of the mantle. A hot proto-Earth produces a larger amount of melt and melt distribution can reach the core of proto-Earth. The melt production from the subsequent impactor flux does not generate a secondary global magma ocean. This raises the question whether and how global magma ocean could have been formed on other planets that did not suffer from a Moon-forming impact scenario.

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