THE FATE OF IRON CORES UPON IMPACT OF DIFFERENTIATED BODIES INTO MAGMA OCEANS. R. Röhlen[1], K. Wünnemann[1,2], C. Maas[3], L. Allibert[1], L. Manske[1] and U. Hansen[3], [1]Museum für Naturkunde, Leibniz Institute for Evolution and Biodiversity Science Berlin, Germany (randolph.roehlen@mfn.berlin), [2]Freie Universität Berlin, Institute for Geological Science, Germany, [3]Institut für Geophysik, Westfälische Wilhelms-Universität Münster, Germany.

Introduction: The moon forming impact and other large impacts during the late accretion phase of the earth likely caused the formation of magma oceans [1]. The fate of material from subsequent impacts into such a magma ocean is of great interest in understanding the composition of Earth's mantle. Most notable hereby is the relatively high concentration of highly siderophile elements in Earth's outer layers [2], which may be explained by the addition of core material from large differentiated impactors during the late accretion phase [3]. To quantify the amount of material that is deposited in the mantle or segregate into the core, a better understanding of the disruption of impactor cores upon impact is of particular importance. Both the break-up into small droplets and the survival of the core in one piece have been discussed in the literature [4] and strongly affect the metal-silicate equilibration and mixing in a magma ocean. The size-frequency distribution of impactor core fragments has already been studied by laboratory and numerical experiments [5,6,7]. In the latter, different numerical approaches have been employed. Mesh-free smoothed particle hydro dynamics (SPH [8,9]) often suffer from insufficient resolutions. Here we use the mesh-based shock physics code iSALE to tackle the resolution problem by implementing a new particle method that allows more accurate tracking of impactor material. In contrast to previous attempts [7], where tracers have been used to estimate the distribution of impactor material in a post-processing step, we use a new approach that allows for mitigating numerical artifacts as a consequence of underresolving fragments of impactor material on a given grid resolution. The ultimate goal is to estimate the size-frequency distribution of impactor cores as a function of impact parameters (core size, impact velocity and angle) and properties of the target (depth, temperature, and viscosity of the magma ocean). Such result can be used in a subsequent step in modelling the mixing of core material in a convecting magma ocean considering also Earth's rotation [10].

Methods: In this study we use the iSALE-2D shock physics code [11,12] assuming an Euler grid. Lagrangian tracers, initialized at defined positions at the beginning of the simulation and then moved according to the velocity of the surrounding material without interacting with it, are often used to track material in simulations. Yet this idea has the disadvantage that the exact fate of the core material has to be reconstructed from the tracers, for example with the stretching ratio model in [7]. Also, small chunks of one material type are subject to numerical artifacts in iSALE. Most notable is a tendency to clump the material together largely independent of the correct physical behavior, as well as artifacts for smaller chunks due to the boundary reconstruction algorithm.

Particle method. To combat these problems, while improving our ability to track the core material of the impactor, we propose a new method to track small chunks of material in iSALE. The simulation starts with one tracer particle in each cell, which are not immediately used to track the material. Instead, we define criteria to identify when numerical artifacts appear. Only when such a criterion is met by a chunk of material of one type, we replace this material with the type of the surrounding matter and simultaneously save the exact volume and mass of the replaced chunk in the nearest tracer particle. This particle then represents the material chunk for the remaining simulation. The advantage of this approach is that it reduces numerical artifacts, while allowing to continue the tracking of the material chunks. Additionally, in contrast to using tracers from the start, they can now represent a fragment of the core that actually formed in the simulation instead of just the matter in its starting cell. One simple criterion used in this method is to find small chunks of the relevant material type by looking at its concentration in individual cells and their direct neighbors. This kind of numerical criterion can be used to reduce the numerical diffusion, as shown below.

Simulation setup. Similar to [7], we use a 200 km diameter dunite projectile with a 100 km iron core inside. The target is a dunite half space, whose upper 900 km behave purely hydrodynamically with no strength or viscosity. Below this is a small solid layer. We varied the resolution between 20 and 80 cells per projectile radius (cppr). The simulations are performed with and without the particle method.

Results: A visual comparison between simulations with and without the particle method for a cppr of 80 is visible in figure 1. The image shows the position of the iron core material 500 s after impact. At this point the transient crater of the impact has already been flooded by the magma ocean and the core material has moved several 100 km deep while breaking apart. The positive x axis shows results without the particle method and the negative x axis with it. The depth and distribution of the core material (yellow) and the tracers (red dots) are very similar for both cases. The main difference is the absence of very small material chunks on the left side, having been replaced by tracer particles that contain the corresponding mass information.

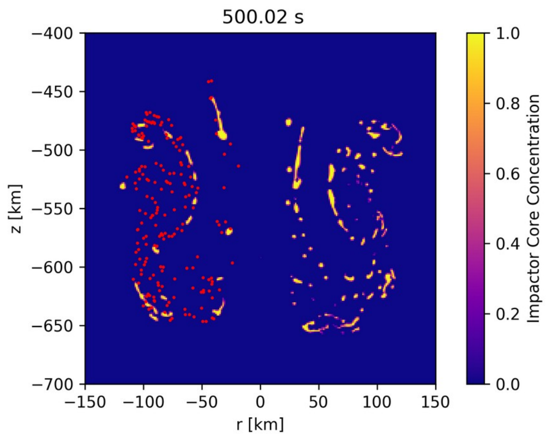

Figure 1: Position of the projectile core material 500 s after impact. The surrounding (blue) material is dunite form the target or projectile mantle. The concentration of iron core material is shown in yellow. The positive x axis shows results from a simulation without the particle method, the negative x axis with it. The tracers used to save volume and mass values are marked in red.

To see if the particle method can be effective in mitigating the numerical diffusion observed, especially for small fragments, the conservation of projectile core mass in the simulation with and without it has been observed. In this comparison, shown in table 1, it is visible that the mass loss due to numerical diffusion is significant. While it decreases with higher cppr and therefore higher resolution, it is still at almost 15% for the highest resolution without the particle method. This quite significant change in matter can be explained by the highly fragmented state of the core material after 500s, as illustrated above. However, if the particle method is used, the numerical-induced loss of matter is reduced by 10% or more.

Table 1: Change of core mass in percent for different cppr without (normal) and with the particle method. Compares initial mass with mass after 500 s.

cppr	Normal	Particle method
20	19.5	9.0
40	17.2	3.1
80	14.5	4.9

Discussion and Conclusion: All conducted simulations show that the core of the impactor breaks into many small fragments while it sinks through the magma ocean after impact. This is in line with the findings in other studies, like [7]. An extensive analysis of the resulting fragment sizes is however limited by the resolution of the simulation, as well as artifacts that have a more pronounced effect on fragments only few grid cells in size. Here we have shown that the proposed particle method can reduce the effect of numerical artifacts. The criterion for the particle method used here focuses only on the concentration in individual cells and their neighbors, which is a useful approach to find very small chunks of material that show high numerical diffusion.

To counter other problems, like the tendency of the code to clump matter together in unphysical ways, other criteria are needed that focus more on the physical parameters of material fragments. These can then be used to decide when a fragment may be broken up by splitting its mass and volume among several tracer particles. Also, the current use of tracers to represent these fragments is based on the assumption that small fragments of material with roughly the same velocity as the surrounding matter will simply be carried along with it. It might be interesting to test this assumption by implementing a way for these particles to keep interacting with the surrounding material in the future. Furthermore, a way for such particles to combine or to be reconverted into material saved in the grid may be helpful, since the core material can only break into smaller particles in the current version.

Acknowledgements: We gratefully acknowledge the developers of iSALE-2D, including Gareth Collins, Kai Wünnemann, Dirk Elbeshausen, Tom Davison, Boris Ivanov and Jay Melosh. This work was funded by the Deutsche Forschungsgemeinschaft (SFB-TRR170, subproject C2 and C4).

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