THE EFFECT OF PLASTIC WORK ON IMPACT-INDUCED MELTING – INTRODUCING AN ADVANCED MELT QUNATIFICATION TECHNIQUE. L. Manske[1,2] and K. Wünnemann [1,2], [1]Museum für Naturkunde Berlin, Leibniz Institute for Evolution and Biodiversity Science, Germany (Lukas.manske@mfn.berlin), [2]Institute of Geological Sciences, Planetary Sciences and Remote Sensing, Freie Universität Berlin, Germany.

Introduction: Impact-induced melt generation is a fundamental process during hypervelocity impact events and collisions on various scale. Studying melt generation is key to better understand the formation history of the terrestrial planets involving processes like accretion, differentiation and degassing that lead to the structure and appearance of the present planets.

In previous studies, impact-induced melt generation is often estimated by semi-analytical models or parameterized results from hydrocode simulations [e.g., 1,2]. These so-called scaling laws often estimate the melt volume as a function of the impactor's kinetic energy or velocity and material properties. However, previous studies found, that the generated melt also depends on the target's properties such as the thermal state or the lithostatic pressure when impactor diameters become larger than 10 km [e.g., 3]. This effect is usually not considered by scaling laws. Furthermore, recent studies empathize that heating due to plastic work and internal friction can significantly contribute to impact melt generation for smaller impactor velocities v_{imp} <10-15 km/s which has often been overlooked in the past [4,5,6].

Here we present an improved and comprehensive method to quantify impact-induced melting in numerical impact simulations. This method is based on the so-called "Peak shock Pressures Method" (PPM) by Pierazzo et al., which uses Lagrangian tracers [1]. We improved the method to account for heating due to plastic work and internal friction as well as target properties such as thermal and pressure gradients in the target. Alternatively, one could use temperatures that are calculated as state variables at any spatiotemporal point to quantify melt, which we refer to as so-called "Final Temperature Method" (FTM). However, the latter method is known to be affected by artificial numerical diffusion causing unphysical spatial spread of heat.

In this study we compare our improved melt quantification method (PPM) with results that are calculated from the temperature field directly (FTM) to assess the effect of numerical diffusion on the latter method. Furthermore, we quantify the contribution of plastic work and internal friction on impact-induced melt generation to narrow down velocity regimes where plastic work and internal friction do or do not significantly contribute to melt generation.

Melt quantification Method: To model hypervelocity collisions, we use the iSALE Eulerian shock physics code [e.g., 7,8]. (Version Dellen). In iSALE the thermodynamic state (EoS) is calculated by look-up tables derived from ANEOS [e.g., 9].

Melt calculation. To determine the volume and distribution of impact-induced melt we calculate the materials final temperature based on the Peak shock Pressure Method PPM. This method derives the materials final temperature T_{fin} from the maximum pressure, P_{peak}, that is experienced during the passage of the shock front. To quantify the melt, this final temperature can then be compared to the melt temperature (*shock melting*). We improved this method by taking not only the materials peak shock pressure into account (P_{peak}), but also the initial (T_0, P_0) and final (P_{fin}) thermal and pressure state. This allows to consider the targets thermal profile and lithostatic pressure and, additionally, enables to quantify decompression melting [3]. Furthermore, we track the energy that is transferred to the material by plastic work and internal friction (*plw melting*). This energy is considered in the calculation of the final temperature T_{fin}. With these updates, the peak shock pressure method accounts for all relevant impact melt generation sources and can be compared to the final temperature method.

Model setup. In this study, we simulate vertical impacts (90°) with an impactor size r_{imp} = 1-50 km onto a planar target with varying impactor velocity v_{imp} = 2.5 - 35 km/s. To reduce the influence of the target properties, we set the initial target and impactor temperature constant to T_0 = 297 K. The melt Temperature is assumed to be constant T_{melt} = 1340 to avoid pressure dependencies resulting in decompression melting. We set the gravity to g = 9.81 m/s^2 to compare the PPM and FTM under cratering conditions on Earth. The impactor is resolved by 50 cells per projectile radius. The target and impactor consist of dunite [10]. Note, with decreasing resolution the effect of artificial numerical diffusion tends to increase significantly.

The effect of impact velocity on melt regimes: It is commonly known that melt generation upon high velocity impacts is enhanced with increasing impact speeds [e.g., 3]. Up to which velocity precisely plastic work dominates over shock melting remains unclear (~10-15 km/s) [4,5,6]. With the introduced method we can separate between shock and plw melting as illustrated in figure 1.

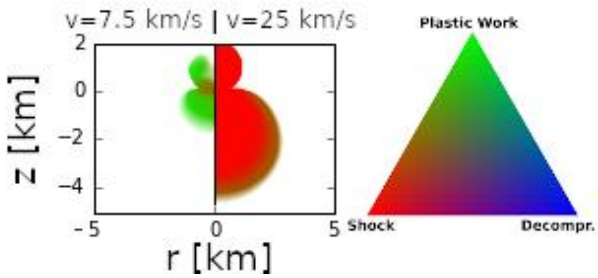

Figure 1. Melt production caused by shock and plw melting mapped back to the pre-impact position for a 7.5 and 25 km/s impact. The color intensity indicates the melt fraction.

Figure 2 illustrate the melting efficiency (Melt volume normalized by impactor volume; top) and the contribution of the different melt sources to the overall melt production (top and bottom) as a function of impactor velocity. We find that shock melting can be neglected at low impact speeds up to $v_{imp} < 5$ km/s. At about $v_{imp} = 11$ km/s shock and plw melting both contribute about 50% to the melt production. With increasing v_{imp} shock melting becomes more dominant until at about 20 km/s where the energy contribution from plw melting becomes constant at about 7%.

PPM vs FTM: Figure 2 illustrates the here presented improved Peak Shock Pressure Method (black line) with the Final Temperature Method (gray dashed line). For a large impactor $L = 50$ km, one can see that the FTM underestimates the melting efficiency for small impact velocities $v_{imp} < 17.5$ km/s and overestimates melting efficiency for large impact velocities $v_{imp} > 20$ km/s compared to the PPM. For a small impactor $L = 2$ km, the melt is underestimated dramatically by the FTM. Additionally for the small impactor, the blue dashed line indicates the melt efficiency by the FTM calculated after the rarefaction wave has passed. Here the results are less affected by numerical diffusion and closer to the results of the PPM. With ongoing time and advection, numerical diffusion causes to smear out the temperature field due to the deformation process during the crater formation. This results into reduced melt volume by smearing out small thermal anomalies caused by small impact velocities so that the temperatures drop below the melt temperature (e.g., small impactors and velocities). Vice versa holds true for large thermal anomalies of high temperatures caused by high impact velocities (e.g., large impactors and velocities; c.f. blue and gray line).

Conclusion: The contribution from plastic work is dominant for impact velocities smaller than 11 km/s and stays constant for large impact speeds larger than 20 km/s at about 7% (for the chosen parameters). Thus, plastic work should not be neglected at impact velocities below 15 km/s. For larger impact velocities one may still consider the ~7% of impact melt by plw melting. The Final Temperature Method becomes inaccurate when examine the final melt distribution. It should only be used after the rarefaction wave has passed. For a more detailed melt quantification we refer to the here presented method.

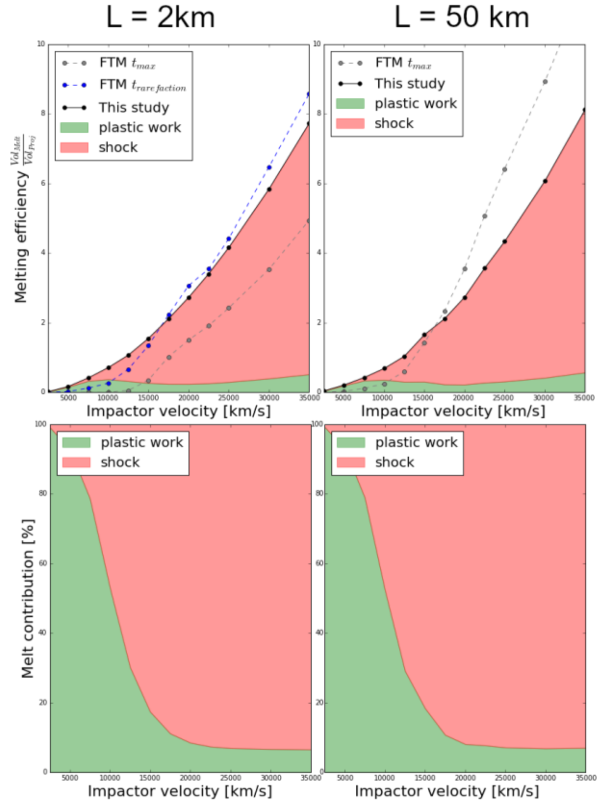

Figure 2. Melting efficiency (top) and energy contribution to the overall melt (bottom) for plw and shock melting as a function of impact velocity. The melt efficiency is plotted for the PPM (black) and FTM (gray; blue).

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