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Melting during planetary collisions: Influence of material properties

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Abstract

In this study, melt production due to planetary collisions is calculated for an accretion history involving more than 400 impacts, as predicted by N-body modelling [1]. Varying material properties in this calculation result in a difference in the amount of energy already available in the target body. It is shown that the pressure dependence of the liquidus temperature has a significant influence on the melting depth.

1. Introduction

The rocky planets in the inner solar system show variation in their isotopic composition that is likely caused by different processes during the formation of the planets. Most likely processes for this are core formation and metal-silicate element partitioning caused by impact heating. To study the influence of these processes during planet formation, a combination of N-body models and compositional models, that calculate the changes in composition due to core formation during the growth stage, is required. For the compositional models, the amount of energy and therefore the potential amount of melting in the growing planet caused by each impact is a critical parameter, as this influences the pressure and temperature conditions of element partitioning. In this study, the amount of melting caused by each impact, as calculated from N-body simulations [1], is determined. Material properties determine the amount of energy already available in a planetary embryo at a specific temperature. The potential error in the amount of melting caused by poorly determined material properties is studied here.

2. Model description

As 3-D models would be too time consuming for more than 400 impacts that typically result from N-body simulations, and 2-D models cannot properly describe non-vertical impacts due to their assumed symmetry, we use the parametrised model as described by Abramov et al., 2012 [2]. This model is based on the dimensional analysis from Bjorkman and Holsapple, 1987 [3] and, assuming a spherical melt volume and taking into account the effect of a non-vertical impact angle, describes the melt volume as:

$$V_{melt} = \frac{\pi}{6} k E_m^{-3\mu/2} \frac{\rho_p}{\rho_t} D_p^3 v^{3\mu} \sin^{2\gamma}\theta \tag{1}$$

To take into account the amount of energy already present in the planetary embryo, the specific energy of melting is expressed as follows [2]:

$$E_m \left(1 - \frac{C_p(T_s + \frac{dT}{dz} d_m)}{C_p \frac{dT_L}{dP} P(d_m) + L_m}\right), \tag{2}$$

where the pressure at depth d_m is calculated from a simple 2-layer model. This expression decreases E_m with the ratio of the energy available at depth and the energy required for melting. Equations 1 and 2 can be solved numerically to determine the depth of melting. Where this depth exceeds the core-mantle boundary (CMB) depth, the parameters are changed to core (iron) values and the equation is solved again to determine how deep melting penetrates into the core.

Table 1: Symbol explanation with values and units.

Symbol	Description	Value/Unit
V_{melt}	Melt volume	km^3
k	Experimental constant	0.42
E_m	Specific energy of melting	kJ/(kg K)
μ	Experimental constant	0.56
ρ_p	Projectile density	3320 kg/m^3
ρ_t	Target density	3320 kg/m^3
D_p	Projectile diameter	km
v	Impact velocity	km/s
γ	Experimental constant	0.66
θ	Impact angle (90 is head-on)	$\circ$
C_p	Specific heat	kJ/(kg K)
T_s	Surface temperature	1650 K
T	Temperature	K
z	Depth coordinate	km
d_m	Depth of melting	km
T_l	Liquidus temperature	K
P	Pressure	GPa
L_m	Latent heat of melting	kJ/kg

3. Results

The first calculation has been done using average values for silicate minerals for the material properties. Thermal structure and material properties are the same for all bodies. The results are shown in Figure 1. The melting depth is given relative to the depth of the core-mantle boundary to eliminate the effect of the embryo size. The timescale on the horizontal axis shows the time of impact as determined by the N-body models.

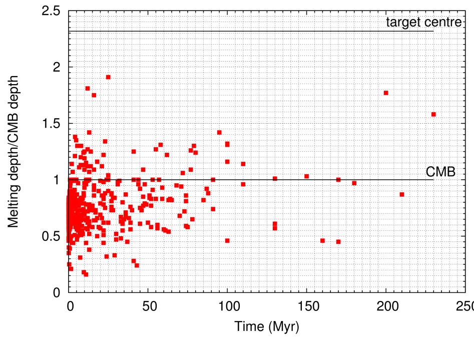

Figure 1: First results showing the ratio of melting depth to core-mantle boundary (CMB) depth for approximately 400 impacts from N-body simulations.

To determine the influence of material properties, we varied the specific heat, latent heat of melting and the pressure dependence of the liquidus temperature within a reasonable range for silicate minerals. Each parameter is varied by a factor of 3. We used the following values:
C_p: 0.5–1.5 kJ kg^{-1} K^{-1}
L_m: 250–750 kJ kg^{-1}
$\frac{dT_l}{dP}$: 50–150 K GPa^{-1}
The results for $\frac{dT_l}{dP}$ are most extreme and are shown in

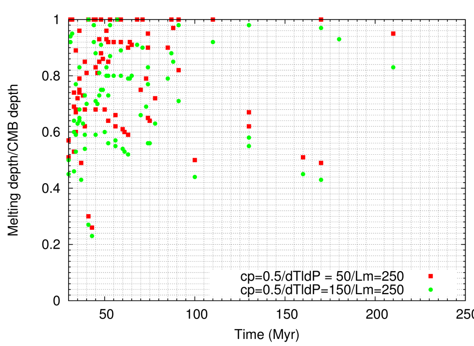

Figure 2: Results showing the difference in melting depth for the two extreme values of the pressure dependence of the liquidus temperature. Only a limited number of impactors are shown for clarity and only mantle melting is considered here.

Figure 2. Only mantle melting is shown and the first 30 Myr of impacts are omitted for clarity. A difference in melting depth of up to 12% can be seen for for example the last impact.

For comparison, the most extreme cases, varying all three parameters are shown in Figure 3. The maximum difference in melting depth is only slightly larger, approximately 16%.

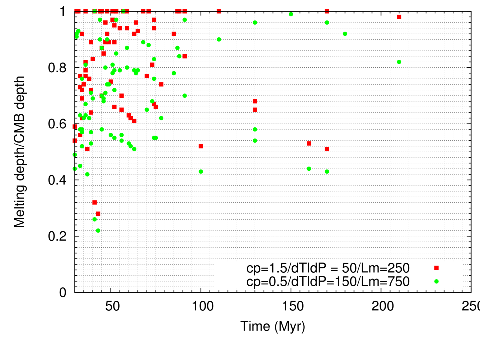

Figure 3: Results showing the maximum melting depth difference that can be achieved with the described range of parameter values.

4. Conclusions & Outlook

The pressure dependence of the liquidus temperature has the largest influence on the depth of melting. This variable is very dependent on the choice of mantle composition and it is therefore important to carefully consider this choice when modelling melting due to planet forming impacts.

Future work will look into the influence of the size of the impactors. In N-body models, the minimum size of the impactors is generally set to approximately Moon-sized bodies to save computation time. However, it may be more realistic to split at least some of these impactors into a number of smaller impact with a small random variation in impact angle and velocity.

References

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