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Creep related compaction of initially porous planetesimals

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Abstract

In the present study, we investigate in which way the internal structure of initially porous planetesimals evolved in their early history. We compute porosity loss of planetesimals due to hot pressing (creep flow) consistently with their thermal evolution. Our results indicate that previous studies (which assumed compaction at the fixed temperature interval of 670-700 K) overestimate compaction and hence underestimate the maximum temperature of planetesimals.

1. Introduction

Compaction of initially porous material prior to melting is an important process that has influenced the interior structure and the thermal evolution of planetesimals in their early history. On the one hand, compaction decreases the porosity resulting in a reduction of the radius. On the other hand, the loss of porosity results in an increase of the thermal conductivity of the material, and thus in a more efficient cooling. Porosity loss by hot pressing is the most efficient process of compaction in planetesimals and can be described by creep flow, which depends on temperature and stress. Hot pressing has been repeatedly modelled using a simplified approach, for which the porosity is gradually reduced in some fixed temperature interval between ≈ 650 K and 700 K (see e.g. [1]-[3]). This approach neglects the dependence of compaction on stress. In the present study (see [4]), we compare this "parametrised" method with a self-consistent calculation of porosity loss via a "creep related" approach.

2. Model

We use our thermal evolution model from previous studies (see [5]) to model compaction of an initially porous ordinary chondritic body and consider four basic packings of spherical dust grains (simple cubic, orthorhombic, rhombohedral, and body-centred cubic). Depending on the grain packing, we calculate the effective stress and the associated porosity change via the thermally activated creep flow:

$$\frac{d\varepsilon}{dt} = A\sigma^n b^{-m} e^{-\frac{E}{\mathcal{R}T}} \tag{1}$$

with the strain ε, the time t, a constant A, the effective stress σ, the grain size b, the creep activation energy E, the gas constant $\mathcal{R}$, the temperature T, and the constants m and n.
For comparison, compaction is also modelled by simply reducing the initial porosity linearly to zero between 650 and 700 K. Since we are interested in thermal metamorphism and not melting, we only consider bodies that experience a maximum temperature below the solidus temperature of the metal phase.

3. Results

Figure 1 shows the final porosity profiles obtained using either parametrised approach (dashed lines) or the creep related one (solid lines) in a sample body with a reference radius of 5 km (in both cases four different initial packings and porosities are considered). Here, the creep related approach for hot pressing results in a less effective compaction in contrast to the parametrised approach (in the latter case the material consolidates completely in the regions where the temperature of 700 K was reached). In our study, we found that for a central pressure of 200 - 300 MPa (equivalent to a planetesimal with a radius of 500 km) the temperature interval is 597 - 690 K, for a pressure of 2 - 3 MPa (equivalent to a planetesimal with a radius of 50 km) it is 645 - 739 K, and for a pressure of 0.02 - 0.03 MPa (equivalent to a planetesimal with a radius of 5 km) it is 740 - 925 K, assuming an activation energy of 356 kJ mol^{-1}.
Variation of further important parameters such as the creep activation energy, the grain size, and the effective stress, also results in distinct compaction

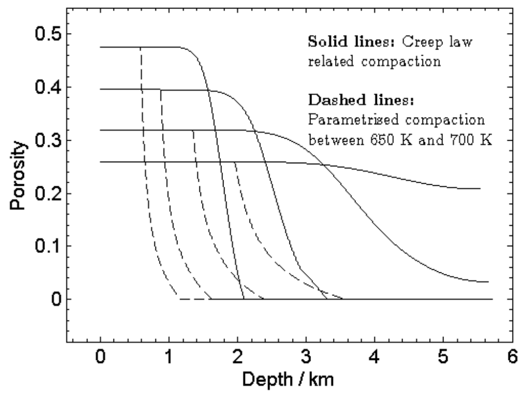

Figure 1: Porosity after the cooling of the body below 300 K as a function of depth. Considered is a body with a reference radius of 5 km (this radius corresponds to zero porosity) which forms at 2.3 Ma relative to the formation of Ca-Al-rich inclusions. Four different packings with the corresponding initial porosities are considered. From top to bottom (at the depth of zero km) the lines (both solid and dashed ones) correspond to the simple cubic, orthorhombic, body-centered cubic, and rhombohedral packing. Note that for the single packings the different porosities in the primordial layer result in a variation of the radius. Also, for a chosen packing, having different final average porosities (i.e. different thickness of the porous layer), the associated solid and dashed lines have different length. This is not obvious here because the dashed lines are overlaid by the solid lines at depth.

scenarios and temperature windows for the closure of pores.

Only for a rather narrow parameter space or pressure range in a planetesimal, compaction occurs approximately between 650 and 700 K as used in the parametrised approach. Depending on the pressure, initial grain size, activation energy and initial porosity, the temperature interval in which planetesimals are expected to compact is rather 500-1000 K.

4. Discussion and Conclusions

For the creep related approach, the temperature interval in which compaction takes place depends strongly on the pressure (and, thus, on the size) of the planetesimal and is not fixed as assumed in the parametrised approach. Depending on the radius, the initial grain size, the activation energy, the initial porosity and the specific packing of the dust grains, the temperature interval lies within 500 - 1000 K. This finding implies that the parametrised approach strongly overestimates compaction and underestimates the maximal temperature. For the cases considered, the post-compaction porous layer retained at the surface, is a factor of 1.5 to 4 thicker for the creep related approach. The difference in the temperature evolution between the two approaches increases with decreasing radius and the maximal temperature can deviate by over 30 % for small bodies.

For some extreme values of E and b, the temperature at which the pores close exceeds even the solidus temperature of the silicates. Significant differences in the interior structure and temperature evolution are the consequence - with the simplified approach compaction is overestimated predicting too low final porosities and thus an unrealistically fast cooling.

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