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A combined diffusion and thermal modeling approach to determine peak temperatures of thermal metamorphism experienced by meteorites

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Abstract

Carbonaceous chondrites are affected to different degrees by thermal and aqueous metamorphism on their parent bodies. However, the degree of alteration has been categorized mainly by relative scales and achieving quantitative information about metamorphic temperature by conventional mineral thermometry is problematic for low petrologic types. We have developed a general approach to estimate the metamorphic peak temperature experienced by type 3 chondrites from diffusion zoning in minerals, and have applied this approach to olivine in type I and type II chondrules of CO3 chondrites.

To obtain metamorphic temperatures from diffusion zoning, we have combined diffusion modeling with thermal modeling of the meteorite parent body. The integrated diffusion coefficient over time (Γ) was identified as a useful parameter to quantify the extent of chemical change by diffusion occurring in a mineral during a given thermal history. Knowing the temperature dependence of the diffusion coefficient, Γ values can be calculated for each thermal history and be compared to the Γ values obtained from diffusion modeling. For thermal histories realistic for the parent body, Γ depends primarily on the metamorphic peak temperature, so that Γ values determined from diffusion profiles in meteorite minerals can be directly related to the metamorphic peak temperature. This general approach is relatively insensitive to uncertainties in the input parameters for the thermal model.

We found that chemical zoning in type I and type II chondrule olivine of the CO chondrites Kainsaz and Lancé was largely influenced by solid state diffusion, which is evident from the observed correlation of zoning anisotropy with the crystallographic orientation. Chemical zoning in type II chondrule olivine is mainly igneous for CO chondrites of petrologic types up to at least 3.2 (Kainsaz) and was influenced only minor by diffusion during parent body metamorphism. Fe–Mg zoning in type II chondrule olivine and around sealed cracks in type I chondrule olivine yields similar Γ values, indicating a formation of both zoning features during a common thermal history on the parent body. In addition, Γ values for type II chondrule olivine correlate with metamorphic grade. The application of this approach on Fe–Mg zoning in type II chondrule olivine of CO3 chondrites yields estimates of maximum metamorphic peak temperatures ranging from 653 to 849 K for different petrologic subtypes. The Fe–Mg zoning of type I chondrule olivine is not consistent with the peak temperature estimates from type II chondrule olivine, suggesting an additional contribution of solar nebular processes to type I chondrule olivine zoning prior to accretion into the parent body.

Keywords: Chondrites; Thermal metamorphism; Diffusion; Olivine; Type II chondrules

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1. INTRODUCTION

1.1. Classification of chondrite metamorphic grades

Chondrites show systematic changes in mineralogical and textural features that have been suggested to result from different degrees of thermal metamorphism on their parent bodies. To systematize these changes, Van Schmus and Wood (1967) introduced the classification of chondrites into petrologic types 1–6. The petrologic type 3 was later recognized to represent the most pristine type, while higher petrologic types represent increasing degrees of equilibration by thermal metamorphism and lower petrologic types increasing degrees of aqueous alteration (McSween, 1979). The original definition of petrologic types was later modified and extended by Sears et al. (1980) who established a further subdivision of petrologic types 3.0–3.9 for the classification of ordinary chondrites based on the thermoluminescence (TL) sensitivity of the bulk rock. TL sensitivity is especially useful to define low petrologic types < 4, but fails to discriminate accurately between petrologic types lower than 3.2 (Grossman and Brearley, 2005). Petrologic subtypes are also defined for some C chondrite groups, including CV and CO chondrites, but the degree of metamorphism for the same subtype is not necessarily comparable between the different ordinary chondrite and carbonaceous chondrite groups (e.g. Scott and Jones, 1990). Grossman and Brearley (2005) therefore used the Cr_2O_3 content of ferroan olivine to refine the classification by establishing a definition of low petrologic types of 3.00–3.15, that can be applied to both ordinary and carbonaceous chondrites. The structural grade of organic matter is also sensitive to thermal metamorphism (e.g. Quirico et al., 2003; Bonal et al., 2006; Busemann et al., 2007) and has been used to define petrologic types (Bonal et al., 2007).

1.2. Estimates of metamorphic peak temperatures

Despite elaborate and detailed classification schemes based on several different methods, petrologic types only represent relative degrees of thermal metamorphism and do not provide direct and quantitative links to the metamorphic thermal histories of chondrites. The metamorphic peak temperatures and thermal histories experienced by chondrites are, however, crucial for the understanding of the thermal evolution of their parent asteroids. In addition, unless the thermal history of meteorites is quantified, it is difficult to clearly distinguish between features in meteorites formed before and after accretion of the parent body. So far, minimum metamorphic peak temperatures of equilibrated ordinary chondrites have been estimated mainly based on the closure temperatures of various mineral thermometers (e.g. Slater-Reynolds and McSween, 2005; Wlotzka, 2005; Kessel et al., 2007). Although a correlation between equilibrium temperatures and petrologic types 4–6 can be found in these studies, the temperature differences between different petrologic types are generally poorly resolved. Applying olivine spinel thermometry to unequilibrated chondrites of types 3–4, Johnson and Prinz (1991) found that the resulting equilibrium temperatures are often close to the mineral crystallization temperatures during chondrule formation, since the chondrule minerals experienced only limited re-equilibration by solid state diffusion during thermal metamorphism. Thus, conventional element exchange thermometry is not applicable to low petrologic types due to the lack of suitable mineral pairs, that equilibrate at low metamorphic temperatures. Cody et al. (2008) showed that the structural grade of insoluble organic matter can be used to determine metamorphic temperatures of unequilibrated chondrites, but there are difficulties in establishing the kinetics of the process and hence this method is based on an entirely empirical calibration (e.g. see also Beyssac et al., 2002).

In contrast, solid state diffusion is a kinetic process that is well-described by physical laws (e.g. Philibert, 1991; Chakraborty, 2008). The chemical zoning of olivine crystals in type II chondrules of CO3 chondrites is also known to correlate with metamorphic grade (e.g. Scott and Jones, 1990) and has been proposed to be the result of diffusive equilibration with the chondrite matrix during parent body metamorphism (Jones and Rubie, 1991). Assuming various cooling rates (0.1–10 K/Ma) in the parent body Jones and Rubie (1991) estimated metamorphic peak temperatures of 410–570 °C for CO3 chondrites by diffusion modeling of FeO zoning in type I and type II chondrule olivine. However, Jones and Rubie (1991) reproduced only the general shapes of the profiles but did not fit measured compositional profiles directly.

A drawback of diffusion modeling is that constraints on the temperature are required to obtain information on time scales (e.g. the duration of an isothermal process or the cooling rate for a non-isothermal process) or vice versa. Metamorphic peak temperatures or cooling rates are, therefore, commonly determined assuming approximated linear (e.g. Jones and Rubie, 1991), asymptotic or exponential (e.g. Ganguly, 1982) cooling histories, where one parameter, either the peak temperature or the cooling rate constant, needs to be estimated. The thermal histories on planetesimals are, however, characterized by both slow heating and cooling in the temperature range close to the peak temperature, where diffusion is most effective. Diffusion during the heating period thus plays a significant role, but is not considered in the approximations commonly used for diffusion modeling. The thermal evolution of planetesimals has been studied by several authors (e.g. LaTourrette and Wasserburg, 1998; Henke et al., 2012) providing detailed information of possible thermal histories of meteorite material on the parent body.

In this study, diffusion modeling for olivine is combined with thermal modeling of the meteorite parent body. This approach allows us to overcome the ambiguity of interpretation in diffusion modeling for non-isothermal processes, since the possible cooling histories and peak temperatures are constrained to combinations that are realistic for the parent asteroid. As a consequence, we can demonstrate that the metamorphic peak temperatures can be estimated directly from diffusion zoning profiles that formed during parent body metamorphism. Olivine zoning in type I and type II chondrules of CO3 chondrites has been reported