DIFFUSION MODELING OF COOLING RATES OF RELICT OLIVINE IN SEMARKONA CHONDRULES.

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Introduction: A quantitative understanding of the formation of chondrules, igneous spherules accreted into chondrites, could yield constraints on the high temperature processes operating in the protoplanetary disk. However, determining their cooling rates from simulation experiments [1,2] is controversial, and diffusion calculations offer an independent approach [3,4]. Here we use diffusive exchange profiles between relict olivine and surrounding melt-grown olivine in Type IIA chondrules to find their cooling rates.

Measurements: We observed several Type IIA chondrules with relict forsteritic olivine grains, in Semarkona MNHN ns2. Composition profiles were measured across the interfaces between relict and epitaxial overgrowth olivine, with 1 micron spacing using Cameca SX100 microprobes. As diffusion in olivine is significantly anisotropic, the orientation of the diffusion profile (the line normal to the relict/ overgrowth interface in Fig. 1) with respect to the crystallographic orientation of the olivines (Fig. 2), was determined using electron back-scattered diffraction (EBSD).

Calculations: We have modeled Fe-Mg and Cr composition profiles across the interface between relict and overgrowth olivine, for two relict grains in the same chondrule 13-36. Assuming that the gradients are due to diffusion developed during cooling of the chondrules, we have used the retrieved values of $\int D(t)dt$ to estimate cooling rate. We adopted the formulation developed by Ganguly et al. [5] using non-linear cooling models in which the temperature changes as a function of time according to either $1/T = 1/T_o + \eta t$ (Asymptotic model) or $T = T_o\exp(-\alpha t)$ (Exponential model), where η and α are constants with dimensions of $K^{-1}t^{-1}$ and t^{-1}, respectively.

Examples of measured zoning profiles of Fe and Cr in one grain (13-36A), as determined by step scanning normal to the core/rim interface, and model fits to the data according to the solution of diffusion equation with initial step function profile across a planar interface of two semi-infinite grains are illustrated in Fig. 3. The value of the diffusion coefficient (D) normal to the core/rim interface was computed from the orientation of the diffusion profile and the measured values parallel to the a, b and c axial directions, as given by [6] for Fe-Mg inter-diffusion in olivine and [7] for Cr. The diffusion coefficients have also been corrected for the effect of $f(O_2)$. The $f(O_2)$ calculated for FIQ and related equilibria according to [8] yields a $\log f(O_2)$ at the estimated crystallization temperature of 1634 C of the melt-grown olivine, indistinguishable from -9.2 bars, the intrinsic $\log f(O_2)$ of Semarkona at the same temperature [4, 9].

The *initial* cooling rate is independent of the chosen cooling model [5]. It is found to be ~400°C/h from modeling Fe-Mg zoning profiles and ~300°C/h from Cr zoning profiles across relict/overgrowth interfaces in two different grains from the same chondrule. The cooling curves are shown for grain A in Fig. 4. The profile lengths are significantly different in these grains, but correction for the effect of diffusion anisotropy yields essentially the same cooling rate for the diffusion of the same species. The cooling rate as function of temperature is given by ηT^2 for the Asymptotic model and αT for the Exponential model, with $\eta = (11.4 - 8.36) \times 10^{-4}\ K^{-1}h^{-1}$ and $\alpha = 0.216\text{-}0.160\ h^{-1}$. Thus, at 1000°C, the cooling rate slows down to 135-185°C/h for the Asymptotic model and 200-275°C/h for the exponential model. If there was any significant diffusion relaxation during the growth of the olivine rims, then the cooling rates would have been even faster than the values given above.

Discussion: Cooling rate is a key parameter which can potentially constrain the heating mechansim and cooling environment of chondrules. Experimental simulation of chondrules shows appropriate textures and olivine zoning for cooling rates between 10 and 1000°C/hr, with the best match for then-available zoning data for 100°C/hr [1,2]. However, oxygen isotope data for a chondrule with relict olivine grains have led to the suggestion of initial cooling rates as high as 10^5 °C/hr [10]. A new model which considers diffusional modification of the Fe-Mg chemical zoning profile during olivine growth shows large vairiations in chondrule cooling rates, from <1°C/hr to >2000°C/hr [4]. Using the methods of Ganguly et al. [5, 11], Greeney and Ruzicka [3] have pioneered the use of diffusion profiles between relict and overgrowth olivine in chondrules to retrieve their cooling rates, but found somewhat discordant results. This may be due to incipient metamorphism in the chondrites chosen and failure to correct for the change of diffusion coefficient with the diffusion direction in different grains. . We have restricted our work to 3.0 Semarkona, using well constrained values for the diffusion coefficients of Fe, Mg and Cr, [6,7], and accounting for the effects of diffusion anisotropy. There are large discrepancies in the available Fe-Mg inter-diffusion data in olivine. However, use of any other diffusion data for Fe-Mg yields cooling rates that have much greater disagreements with those obtained from modeling the Cr zoning profile. The initial cooling rate found for chondrule 13-36, 300-400°C/hr, is consistent with experimental simulations and (some of) the results of [4]. It is also consistent with certain chondrule formation models, e.g. nebular shocks. We will extend this approach to multiple chondrules in Semarkona, and also investigate diffusion profiles of other minor elements for which high quality diffusion data are available for olivine.

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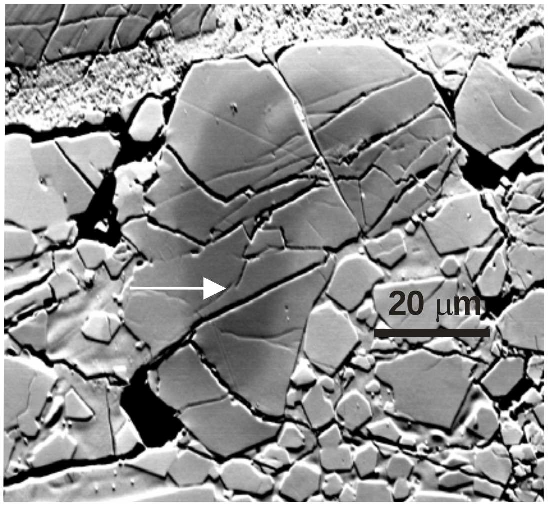

Fig. 1 Backscatter electron image (BSE) of relict olivine A in Semarkona chondrule 13-36.

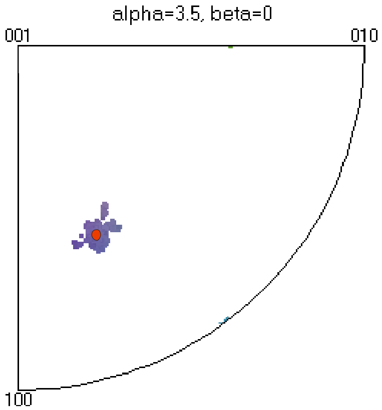

Fig. 2 Orientation of the diffusion profile in crystal coordinates. Angles between diffusion profile and a,b and c are 36.6°, 68.5° and 62°.

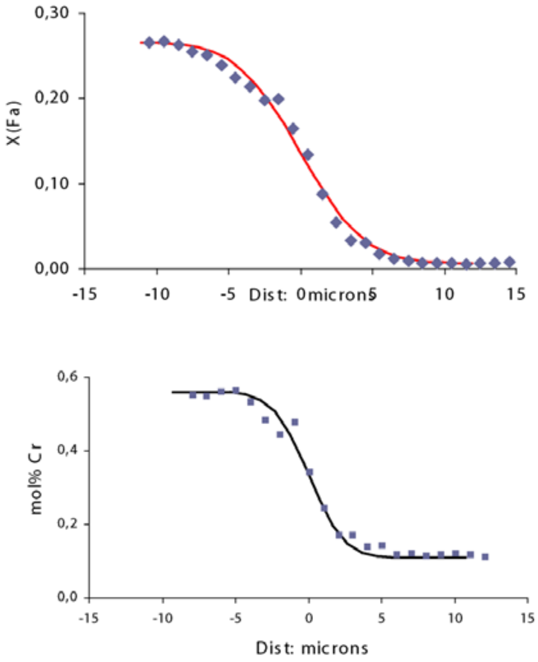

Fig. 3 Measured compositional zoning (symbols) across relict core-rim overgrowth of olivine chondrule in Semarkona sample 13-66A. The solids are model fits according to the solution of diffusion equation.

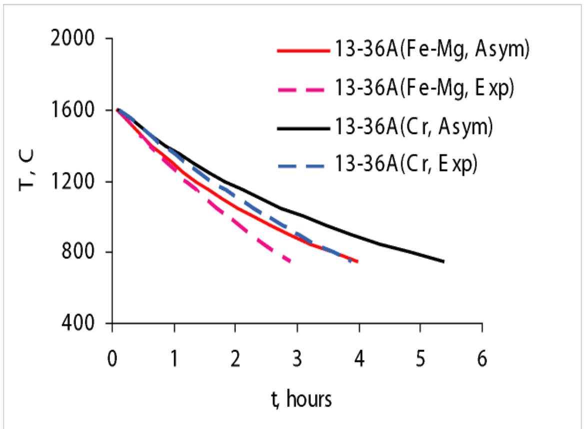

Fig.4 Temperature-time profiles for relict olivine chondrule in 13-36A, as retrieved from modeling Fe-Mg and Cr zoning profiles (Fig. 3). Asym: asymptotic and Exp: exponential cooling models.