MODELING OF TYPE II CHONDRULE COMPOSITIONS IN CO3 CHONDRITES – CONSTRAINTS ON THE CONDITIONS OF CHONDRULE FORMATION AND THERMAL METAMORPHISM.

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Introduction: Minerals in porphyritic type II chondrules of unequilibrated chondrites exhibit chemical zoning, that formed by fractional crystallization and solid state diffusion processes during chondrule formation. Simulating the formation of these mineral zoning patterns by thermodynamic and kinetic modeling allows the determination of chondrule cooling rates [1]. It has been suggested that most type II chondrules formed by partial melting of their precursors [2]. Such partial melting might have occurred because the peak temperature of the heating event did not exceed the bulk chondrule liquidus temperature. Alternatively, the temperatures might have exceeded the liquidus temperature but the cooling rates were fast enough to kinetically inhibit complete melting of the chondrule. To evaluate which of these two melting scenarios is more realistic for type II chondrules, we modeled the chemical zoning in olivine and spinel crystals of type II chondrules in the CO3.0 chondrite NWA 7103.

In CO3 chondrites of higher petrologic subtypes, the chemical zoning in type II chondrule minerals might have been altered during thermal metamorphism on their parent asteroid. To evaluate the influence of thermal metamorphism on the bulk chondrule compositions and the mineral zoning, we also modeled bulk and mineral compositions of type II chondrules in several type 3.2-3.6 CO chondrites.

Methods: *Analytical methods.* We measured the zoning of Fe, Mg, Ca, Mn, Al and Cr along traverses across olivine and spinel crystals of type II chondrules in CO3 chondrites using EMPA and obtained bulk chondrule compositions and mineral modal abundances from compositional EMPA maps. The crystallographic orientation of the traverses measured across olivine crystals was determined by EBSD analysis. Fe^{2+}/Fe^{3+} ratios of spinel crystals were determined stoichiometrically from the EMPA data. *Modeling approach.* To simulate the process of fractional crystallization from the bulk chondrule melt, we used the MELTS program [3], [4], that allows to calculate the volumes and compositions of minerals crystallizing from a melt of given composition at discrete temperature steps during cooling. Using the MELTS output data and assuming spherical crystal shapes, we calculated radial zoning profiles, that can be compared to measured compositional traverses. Simultaneously to crystal growth, the mineral composition is modified by solid state diffusion. To account for this process, we developed a numerical model to simulate the modification of the chemical zoning by diffusion at each temperature step during crystal growth, assuming an exponential cooling history. Applying this modeling procedure, the zoning patterns measured in olivine and spinel were fitted using the chondrule cooling rate as fitting parameter.

Results: The mineral modal abundances of all studied type II chondrules could be reproduced with MELTS, which suggests that the chondrules formed by closed system fractional crystallization of the bulk chondrule melt. The analytically determined Fe^{2+}/Fe^{3+} ratios in spinel are consistent with oxygen fugacities 1 log unit below the IW buffer, which is consistent with previous estimates of type II chondrule redox conditions [5]. The zoning patterns in type II chondrule olivine and spinel crystals of the CO3.0 chondrite NWA 7103 are consistent with partial melting at subliquidus temperatures and slow cooling in the order of a few K/h.

The olivine zoning in CO3.2-3.6 chondrites yields similar cooling rates consistent with subliquidus partial melting, which indicates that they experienced only minor compositional changes during parent body metamorphism. In contrast, the spinel zoning yields unrealistically low cooling rates in the order of a few K/day to K/year. These cooling rates vary systematically with the petrologic subtype of the sample, which indicates that the spinel compositions in CO3.2-3.6 chondrites were systematically altered during parent body metamorphism. We suggest that the cooling rates inferred from olivine can be used to reconstruct the igneous zoning of spinel. The misfit between the measured (metamorphosed) and the modeled (igneous) spinel compositions is finally used to quantify the degree of thermal metamorphism in CO chondrites.

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