**Chondrule thermal history: an approach based on NanoSIMS analysis of short diffusion profiles in melt inclusions.**

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**Introduction**

Chondrules are major constituents of most chondrite groups and understanding their formation is a key objective in the field of meteorites. It is generally believed that chondrules formed in rapid heating events in which solid precursor materials underwent partial melting, followed by relatively fast cooling. Conventionally, the setting for chondrule formation is envisaged to be the nebula, but the exact mechanisms involved are not agreed upon. Several alternatives exist, including e.g. the passage of different types of shock-waves, lightning, planetesimal collision and X-wind dynamics [1]. In order to understand better the dynamics of chondrule formation and constrain the chondrule forming mechanism(s) it is essential to know in greater detail their thermal history, i.e. rate at which the chondrules cooled subsequent to reaching the peak temperature during their formation. The thermal history of chondrules is a complex issue because the cooling process encompasses both crystal nucleation and growth from a melt constantly changing composition due to gas-melt exchange reactions [2] as well as solid-state, diffusion-controlled phase-transformation and crystal growth. For several decades efforts to constrain cooling rates of chondrules have been focused on chondrule textures and experimental petrology [3], calculation of diffusion profiles in zoned olivine crystals [4], or elemental diffusion between two adjacent phases [5].

We are attempting to constrain chondrule cooling rates from short diffusion profiles in melt inclusions captured in olivine crystals. This method has roots in geochemistry and terrestrial petrology where calculation of basalt cooling rates can be based on diffusion profiles from melt inclusions captured in minerals [6]. The melt inclusions are assumed to represent the melt from which the host crystal grew. When the temperature drops, a boundary layer forms at the interphase between the host crystal and the melt inclusion. Various elements diffuse across this boundary layer, in and out of the host crystal at different rates, depending on their respective diffusion- and partition coefficients. Diffusion profiles measured for different elements diffusing from the same melt inclusion therefore offer an overdetermined solution to the diffusion equation and a potentially robust cooling rate determination at temperatures above 1000°C. (Below this temperature, diffusion becomes ineffective for the elements discussed here). For chondrules, however, the major obstacle for this method has been the small linear dimension of the diffusion profiles, typically a few micrometers, inappropriate to standard electron microprobe analyses. With the development of the NanoSIMS, which offers simultaneous detection of up to 5 isotopes with high-precision and a spatial resolution better than 150 nm, this obstacle is now removed. Here we present preliminary NanoSIMS datas for diffusion profiles across the boundary layer and into the host crystal for around 30 melt inclusions in FeO-rich chondrules in Semarkona (LL3 chondrite).

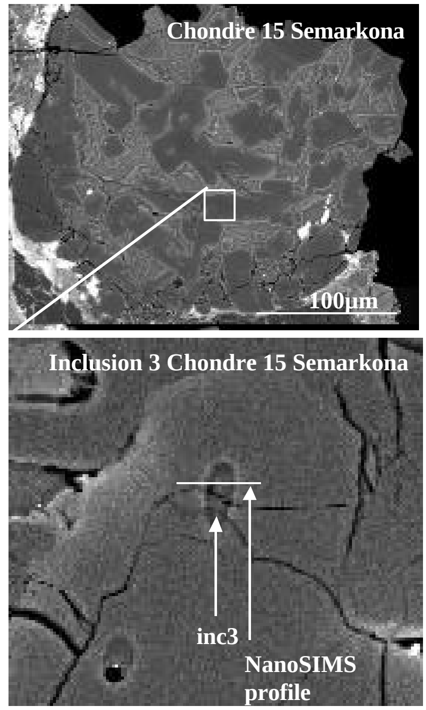


Fig 1: BSE images of inclusion 3 of chondrule 15 in Semarkona

**Samples and analysis:** Based on SEM mapping, type-II chondrules with olivine porphyritic textures were selected from Semarkona. Olivines, mesostasis, melt inclusions and other phases in chondrules were analysed with electron microprobe (CamecaSX100 at Jussieu, Paris). Selected chondrules display distinct differences in olivine grain shape and are suspected to have experienced different thermal histories [7]. Olivine grains in the selected chrondules are all FeO-rich (Mg#=74.78±5.46) and relatively CaO-rich (0.1± 0.05). Melt inclusions are $SiO_2$ and $Al_2O_3$-rich (around 70 and 10 wt% respectively). Their compositions vary from chondrule to chondrule and is usually different from the surrounding residual melt in the host chondrule, which is usually richer in FeO, $Al_2O_3$ and $Na_2O$ and poorer in MgO and CaO. Even within the same host olivine crystal, two melt inclusions can have different compositions, although these compositional differences are small. The melt inclusions are amorphous glass and contain no metallic Fe or crystals. Their sizes (visible diameter) range from 3-15 µm and have generally an ovoid shapes. (In comparison, melt inclusions in terrestrial basaltic olivines range in size from ~5 to >100 µm, with most being smaller than 10 µm [8-9].) The boundary layer at the interface between the melt inclusion and the host olivine crystal has a typical width of 1-3 µm.

Microprobe analysis were used as internal standard for the subsequent NanoSIMS analyses. With the NanoSIMS at the Muséum National d'Histoire Naturelle in Paris, an $O^-$ primary beam was focused onto the selected targets with a spatial resolution better than 150 nm. Chemical maps and linescans across melt inclusions and into host olivine crystals were produced for $^{24}Mg^+$, $^{28}Si^+$, $^{40}Ca^+$, $^{52}Cr^+$ and $^{56}Fe^+$ at a mass resolving power around 4000. Typical dimensions of linescans are 25-10 µm (Fig. 2) and 40-15µm² for chemical maps (Fig. 3). Analytical precision is on the order of 1%.

**Results:** Moving from the host olivine crystal into the melt inclusions, the diffusion profiles obtained with the NanoSIMS typically show an increase of Si and Ca, and a decrease in Mg, Cr and Fe (Fig.2). Diffusion profiles are symmetrical around the inclusions. At the spatial resolution of the NanoSIMS, we obtain about 20-30 analysis for a typical boundary layer. Solutions to the diffusion equation will be fitted to the data sets for different thermal histories and cooling rates will be estimated. Consistency checks will be made for cooling rates obtained for different elemental diffusion profiles surrounding the same melt inclusion, for melt inclusions within the same and in different host olivine crystals and between different chondrules. Cooling rate determination based on these data sets are in progress.

**References:** [1] Boss A. P., (1996) In *chondrules and protoplanetary disk* (eds R. H. Hewins, R. H., Jones and E. R. D. Scott) Cambridge university press, pp257-263 [2] Libourel G. et al., (2005) *LPS XXXVI* abstract #1877 [3] Hewins R. H. et al., (2005) *In Proceedings of the Astrophysical Society of the Pacific Conference Series 341*, 286-316 [4] Miyamoto M. et al., (2004) *67th Annual Meteoritical Society Meeting*, Abstract #5119 [5] Jaoul O. and Sautter V., (1999) *Physics of the Earth and Plantary interiors 110*, 95-114. [6] Danyushevsky L. V. et al., (2002) *Journal of Petrology 43*, 1651-1671 [7] Faure F. et al., (2003) *Contrib. Mineral. Petrol. 145*, 251-263 [8] Thomas J. B. et al., (2002) *GCA 66*, 2887-2901. [9] Tettike T.et al., (2004) *Lithos 78*, 333-361.

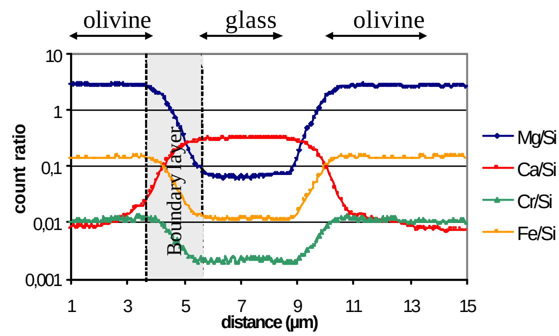


Fig. 2 : NanoSIMS linescan result for inclusion 3 in chondrule 15 (Semarkona). The linescan is made of 144 analysis points on 14 µm.

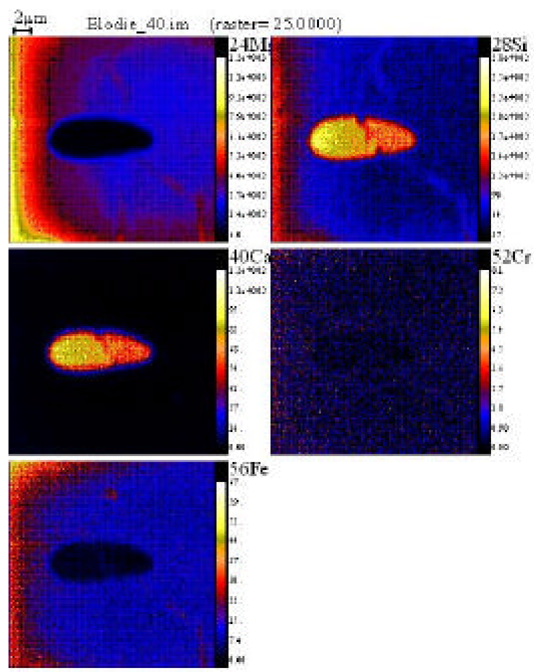


Fig. 3 : NanoSIMS image of inclusion 3 of chondrule 15 (Semarkona)