COOLING RATE OF A TYPE I CHONDRULE FROM THE RENAZZO CR2 CHONDRITE INFERRED FROM Cu AND Ga DIFFUSION PROFILES IN METAL GRAINS. N. Chaumard[1], M. Humayun[2], B. Zanda[1], and R. H. Hewins[1,3], [1]LMCM, MNHN, UMR 7202 – CNRS, 61 rue Buffon, 75005 Paris, France (nchaumard@mnhn.fr), [2]Department of Earth, Ocean, and Atmospheric Science & National High Magnetic Field Laboratory, Florida State University, 1800 E. Paul Dirac Drive, Tallahassee, FL 32310, USA, [3]Department of Earth and Planetary Sciences, Rutgers University, Piscataway, NJ 08854, USA.

Introduction: Chondrules are ubiquitous components of carbonaceous chondrites (CCs) [e.g. 1]. Different mechanisms have been proposed for chondrule formation [e.g. 2–9]. However, these mechanisms were suggested on the basis of cooling rates estimated for Type II (oxidized) chondrules, abundant only in ordinary chondrites, whereas CCs are dominated by Type I (reduced) chondrules. In order to provide new constraints on the heating mechanisms that prevailed throughout the protoplanetary disk in the early Solar System, we determined the cooling rates of a Type I chondrule in the Renazzo CR2 chondrite.

Since metal grains (Fe-Ni alloys) are abundant in association with chondrules [10], we used the method developed by [11] based on Cu and Ga zoning profiles measured by LA-ICP-MS in metal lumps attached to Type I chondrules. Volatile siderophile elements initially present in metal (e.g. Cu, Ga, and Ge) would be evaporated during a melting event then subsequently re-condensed at the exterior of metal grains [e.g. 12–14], and diffused inwards. Thus, analysis of Cu and Ga diffusion profiles can supply constraints on the high temperature event that formed Type I chondrules and their solid-state thermal history.

Methods: To avoid a possible under-estimation of cooling rates due to the random sectioning of metal grains, a fragment of Renazzo was imaged by CT scanning using a v|tome|x 240L from GE Sensing & Inspection Technologies Phoenix X|Ray in order to measure Cu and Ga diffusion profiles passing through the center of metal grains. Thus, we used X-ray tomography to locate Type I chondrules surrounded by large metal grains (Fig. 1). Then, we cut a fragment close to the equatorial planes of selected metal grains on Type I chondrules for further analyses. Finally, we polished our section until an equatorial plane of a metal grain corresponded to the polished surface of our sample.

SEM-BSE imaging and EDS analysis were obtained using a Tescan VEGA II LSU electron microscope. Laser ablation ICP-MS analyses were performed at Florida State University using a New Wave UP193 FX excimer laser ablation system coupled to a Thermo Element XR ICP-MS. Four diffusion profiles were measured through the centers of two metal grains (Fig. 1), using a 15 μm spot size, 5 $\mu m.s^{-1}$ speed, 50 Hz repetition rate, 100% power output (1.55 $GW.cm^{-2}$). Standards used were North Chile (Filomena) IIA iron meteorite, Hoba IVB iron meteorite, and NIST SRM 1263a steel. For a given element, each diffusion profile is characterized by a diffusion length-scale determined numerically.

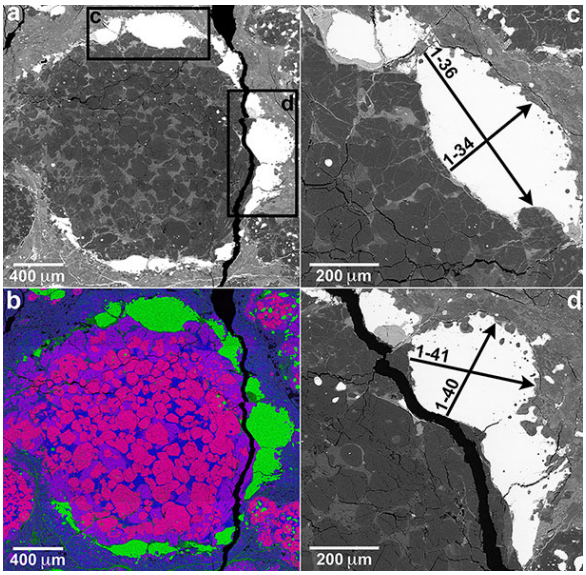

Figure 1: BSE image (a) and RGB compositional map (R=Mg G=Fe B=Si) (b) of the Type I chondrule from Renazzo analyzed in this study. (c) and (d) Higher magnification of the boxed regions in (a) showing laser tracks made by LA-ICP-MS.

Results: We observed chemical zonations for Cu and Ga in all profiles measured, also displaying practically ideal U-shaped profiles (Fig. 2). Diffusion length-scales vary between 35 and 120 μm for profiles 1-41 and 1-36, respectively. Edges of metal grains are enriched in Cu and Ga, with maximal contents measured at ~140 and ~12 ppm, respectively, while cores are depleted in these volatile siderophile elements relative to the edges (~0.20 ppm Cu and ~0.05 ppm Ga).

Since Cu diffuses more slowly than Ga at T>1500 K whereas it is the opposite at T<1500 K [15], we are able to provide an estimation of the temperature at which zoning profiles measured here were formed (*T*p) (Fig. 3). For all zoning profiles, ranges and means of *T*p and cooling rates associated are reported in Tab. 1. Cooling rates are calculated from Cu diffusion profiles as ~4–65 $K.h^{-1}$ for peak temperatures of 1530–1630 K,

with an upper limit of ~0.1–520 K.h^{-1} for a larger range of temperatures of 1273–1800 K (Fig 4).

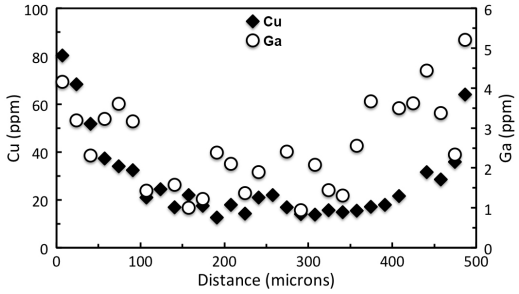

Figure 2: U-shaped zoning profile of Cu and Ga for the 1-36 laser track (see Fig. 1 for location).

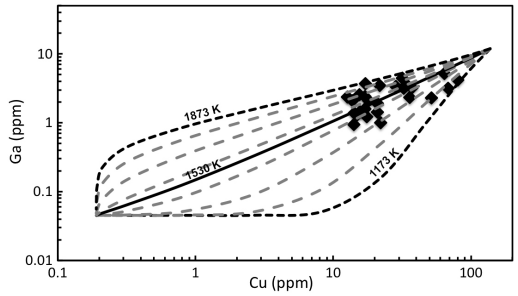

Figure 3: Ga vs. Cu for the diffusion profile 1-36 (diffusion length-scale = 120 μm), as a function of temperature from 1873 K to 1173 K in 100 K increments.

Profile	Diffusion length-scale (microns)	*T*p (K)		Cooling rate (K.h^{-1})	
		Mean	Max. possible range	Mean	Max. possible range
1–34	55	1630	1473–1800	50	9–210
1–36	120	1530	1273–1800	4	0.1–45
1–40	80	1530	1373–1673	9	1–35
1–41	35	1573	1373–1800	65	6–520

Table 1: Diffusion length-scale, *T*p, and cooling rates [8, Eq. (7)] calculated for each zoning profile measured in this work.

Discussion: The two metal grains analyzed for this Type I chondrule argue for a similar solid-state history. Cooling rates estimated here are similar to those calculated from six metal lumps in the Acfer 097 CR2 chondrites by [11], 0.5–50 K.h^{-1} for *T*p ~ 1473 K with a maximum possible range of 0.1–400 K.h^{-1} for *T*p ~ 1200–1800 K, and are close to those obtained from pyroxene exsolution in Type I chondrules from CCs [16, 17]. These results are consistent with cooling rates predicted by shock models proposed for chondrule formation (~10–300 K.h^{-1}, [e.g. 4]), and to a lesser extent by the X-wind model [e.g. 8] that seems only to be able to explain the lowest cooling rates (~<100 K.h^{-1}).

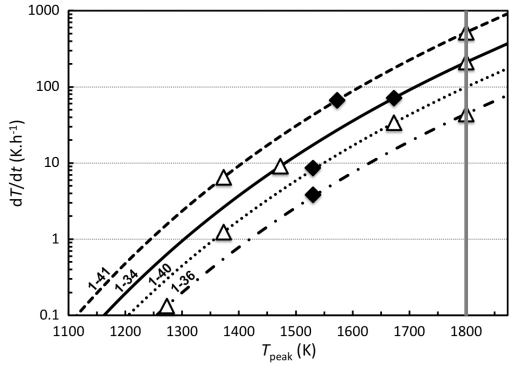

Figure 4: Cooling rates vs. peak temperatures calculated from the four diffusion profiles of Cu measured in this work (see Fig. 1 for location). Diffusion length-scale are 35 μm for the 1-41 profile, 80 μm for 1-40, 120 μm for 1-36, and 55 μm for 1-34. The melting point of Fe-Ni alloys is shown as the 1800 K line. Empty triangles indicate the upper and lower limit of the maximal possible range of *T*p and cooling rates, while filled diamonds correspond to mean values of *T*p and cooling rates for each diffusion profiles.

Conclusion: Cooling rates calculated here appear to be consistent with the predictions supplied by shock models and at variance with the higher cooling rates implied by a lightning model [e.g. 9]. Despite the fact that our quantitative results seem to indicate a similar solid-state thermal history for Type I chondrules in CCs, further systematic studies of cooling rates from metal and silicates could better constrain the high temperature event at the origin of chondrule formation.

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