

EVALUATING CHONDRULE FORMATION MODELS AND THE PROTOPLANETARY DISK BACKGROUND TEMPERATURE WITH LOW-TEMPERATURE, SUB-SILICATE SOLIDUS CHONDRULE COOLING RATES. D. L. Schrader¹, R. R. Fu², and S. J. Desch³. ¹Center for Meteorite Studies, School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287, (schraderd@asu.edu), ²Lamont-Doherty Earth Observatory, Columbia University, PO Box 1000 Palisades NY 10964, ³School of Earth and Space Exploration, Arizona State University, PO Box 871404, Tempe AZ 85287.

Introduction: Constraining the complete thermal history of chondrules is essential to determining their formation mechanism(s) and the conditions of the protoplanetary disk during chondrule formation. Chondrule cooling rates based on silicate compositions, textures, and crystallization experiments conservatively range from $>5000^{\circ}\text{C/hr}$ above the silicate liquidus ($>\sim 1527^{\circ}\text{C}$), to $5\text{--}3000^{\circ}\text{C/hr}$ between the silicate liquidus and solidus ($\sim 1527\text{--}1127^{\circ}\text{C}$) [1–4]. On average, chondrules cooled at rates of $10\text{--}1000^{\circ}\text{C/hr}$ between the silicate liquidus and solidus [2]. These cooling rates have been used to test the validity of numerous models for chondrule formation [e.g., 4].

However, these chondrule cooling rates are limited as they only apply above the silicate solidus ($>1127^{\circ}\text{C}$). Chondrule cooling rates below the silicate solidus are not well constrained despite some previous studies [e.g., 5,6]. Sulfides provide a potential indicator of cooling rates below $\sim 950^{\circ}\text{C}$ (Fe,Ni–FeS eutectic; [7]), as some sulfides cooled from immiscible liquids after silicate crystallization [5,8]. The textures of metal-troilite grains in LL chondrites, compared with experimental products, indicate chondrule cooling rates at a temperature of $\sim 1000^{\circ}\text{C}$. This analysis indicates minimum cooling rates of 100°C/hr and much higher maximum rates for grains with a eutectic texture [5]. Experimental analogs to metal-sulfide grains within Renazzo-like carbonaceous (CR) chondrites suggest cooling rates on the order of 3000°C/hr are possible [6]. These sulfide-cooling rates are similar to those constrained between the silicate liquidus and solidus.

We aim to constrain chondrule cooling rates at temperatures below 1000°C by studying sulfide assemblages in un-metamorphosed chondrites and comparing them to sulfides prepared in the laboratory. The sulfides pyrrhotite $[(\text{Fe,Ni,Co,Cr})_{1-x}\text{S}]$ and pentlandite $[(\text{Fe,Ni,Co,Cr})_{9-x}\text{S}_8]$ form over a range of conditions, including both high- and low-temperature processes. Pyrrhotite-pentlandite intergrowths can form via aqueous alteration [e.g., 9], cooling of a primary high-temperature Fe-Ni-S melt (pentlandite starts to exsolve $\sim 610^{\circ}\text{C}$), thermal metamorphism of a Fe-Ni-S assemblage $>610^{\circ}\text{C}$ and subsequent cooling, or annealing between ~ 600 and 200°C [e.g., 10–13]. Here we focus on the formation of pyrrhotite-pentlandite intergrowths that formed during chondrule cooling between 600 and 400°C [8,14], well below the silicate solidus.

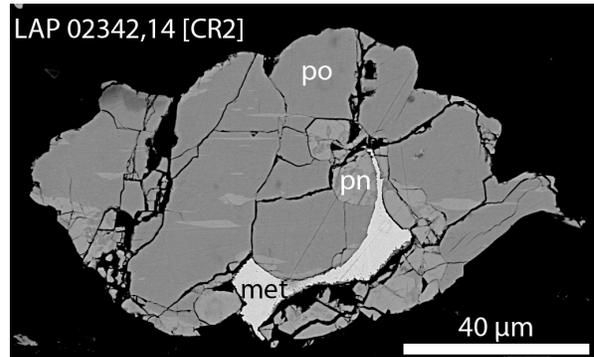


Figure 1. Sulfide assemblage containing pyrrhotite (po), pentlandite (pn), and Fe,Ni metal (met) in LAP 02342,14 (CR2).

Analytical: Sulfide-bearing opaque assemblages were studied in FeO-rich (type II) chondrules from the CM2 Mighei, the LL3.00 Semarkona, and 8 CR2s; Elephant Moraine (EET) 87770, Gao-Guenie (b), Graves Nunataks 95229, LaPaz Icefield (LAP) 02342, LAP 04720, Pecora Escarpment (PCA) 91082, Queen Alexandra Range 99177, and Yamato 793495 (Fig. 1).

Thin sections were studied via optical microscopy, an FEI Nova NanoSEM 600 scanning electron microscope and a JEOL 8900 Superprobe electron probe microanalyzer (EPMA) at the Smithsonian Institution, and a Cameca SX-50 EPMA at the University of Arizona (analytical data from [8,14]). Sulfide bulk compositions were determined by modal recombination analysis using analyses of individual mineral phases via EPMA combined with modal mineralogy (obtained in Adobe Photoshop®) and phase densities [e.g., 3,8,15]. Bulk compositions of 41 sulfide-bearing opaque assemblages from 14 chondrules in CR chondrites were determined by [8]. The bulk composition of four sulfides from Semarkona and Mighei, using EPMA data from [14], were determined for this study. Of these 45 grains, only 12 had the appropriate sulfide phases and bulk composition to estimate cooling rates.

Results: Through a comparison of natural pyrrhotite-pentlandite assemblages to similar experimental assemblages synthesized by [13], we are able to estimate cooling rates for sulfide assemblages in chondrules. Using laboratory cooling experiments of Ni-rich Fe-Ni-S charges, [13] determined that the cooling rate is related to bulk composition and the abundance of pentlandite exsolved. These cooling experiments

utilized three different starting compositions for the charges (from $\text{Fe}_{0.9}\text{Ni}_{0.1}\text{S}$, $\text{Fe}_{0.8}\text{Ni}_{0.2}\text{S}$, and $\text{Fe}_{0.7}\text{Ni}_{0.3}\text{S}$), and were cooled from 700°C to 100°C over 24 hrs but were observed at different time steps. Depending on the bulk composition and the cooling time the sulfides contained different abundances of pentlandite [13].

Table 1. Estimated minimum sulfide cooling rates from type II chondrules

Meteorite	Chondrule	Type	Ablg.	°C/hr
CR2				
EET 87770,31	Ch1	POP	A4	344
EET 87770,31	Ch1	POP	A6	49
EET 87770,31	Ch2	POP	A4	70
EET 87770,31	Ch3	POP	A2	48
Gao-Guenie (b) UA2301,1	Ch1	PO	A5	48
Gao-Guenie (b) UA2301,1	Ch2	BO/PO-comp	A5	95
Gao-Guenie (b) UA2301,1	Ch12	POP	A1	79
LAP 02342,14	Ch1	POP	A1	313
PCA 91082,15	Ch1	POP	A3	84
PCA 91082,15	Ch1	POP	A7	109
LL3.00				
Semarkona USNM1805-17	Ch3	POP	OA9	81
Semarkona USNM1805-17	Ch3	POP	OA10	70

Chondrules (Ch) and sulfide assemblages (Ablg.) from [8,14].

PO = porphyritic olivine; PP = porphyritic pyroxene; POP = porphyritic olivine pyroxene; BO = barred olivine; comp = compound chondrule.

By matching the pentlandite-bearing natural sulfides to similar experimental products, we estimate ΔT (change in temperature) and a Δt (change in time) and obtain approximate cooling rates. This comparative analysis results in estimated cooling rates between ~50 and ~340°C/hr, with a mean of ~120°C/hr (Table 1). These rates suggest the chondrules cooled between 600 and 400°C in ~0.5 to ~4 hrs.

Cooling rates within individual chondrules vary by up to an order of magnitude (i.e., 49 vs. 344°C/hr; Table 1). Assuming chondrules cooled uniformly, the sulfides in two chondrules with similar cooling rates indicate uncertainties are $\sim\pm 25^\circ\text{C/hr}$ (84 vs. 109°C/hr; 70 vs. 81°C/hr). The difference in sulfide cooling rates from EET 87770 Ch1, 49 vs. 344°C/hr, indicate a conservative uncertainty is an order of magnitude.

Most sulfides studied here had a higher bulk Ni content and/or more exsolved pentlandite than the experiments. Therefore, we were only able to constrain the cooling rates for 12/45 sulfides. However, samples with higher bulk Ni content exsolve more pentlandite faster than sulfides with less bulk Ni [13]. Therefore, we suggest the remaining sulfides cooled on similar or faster timescales than those constrained here.

Discussion: These sub-silicate solidus cooling rates provide a testable constraint on chondrule formation models. One proposed model of chondrule formation is heating via current sheets and resulting short-circuit instabilities [16,17]. A caveat of this model is that the background temperature of the protoplanetary disk must be high enough to facilitate thermal ionization, a minimum of 800K (~527°C) [17,18]. If an initial background temperature of 850K (~577°C) is considered short-circuit instability models lead to peak temperatures of 1600K (~1327°C), high enough to melt precursor chondrule silicates [17].

Chondrule cooling rates should slow down as they approach the background temperature of the protoplanetary disk. Average chondrule cooling rates between the silicate liquidus and solidus (~1527–1127°C) were 10^1 – 10^3 °C/hr [1–4]. Therefore, the rapid chondrule cooling rates of $\sim 10^2$ °C/hr between 600 and 400°C suggest that the background temperature of the protoplanetary disk was well below 400°C.

Current sheet models require a background protoplanetary disk temperature of at least ~527°C, which would be stable before and after peak temperatures of chondrule formation are reached [17,18]. Since the background temperature of the protoplanetary disk during chondrule formation was below 400°C, we find that the conditions did not exist to facilitate heating via current sheets and resulting short-circuit instabilities.

Conclusions: Chondrule cooling rates between 600 and 400°C are determined to be on the order of $\sim 10^2$ °C/hr. These rapid cooling rates are consistent with the unidirectional remanent magnetization observed between 450°C and 725°C in Semarkona chondrules [19] and suggest a protoplanetary disk background temperature well below 400°C. This low temperature is inconsistent with chondrule formation via current sheets and resulting short-circuit instabilities. As additional evidence for this conclusion, the nebular magnetic field intensity recorded in chondrules was found to be lower than expected from current sheets [19], while the ionization state of hot gas in the protoplanetary disk was found to be inconsistent with heating via current sheet instabilities [18]. Further modeling is required to apply these sub-silicate solidus cooling rates and the protoplanetary disk background temperature to other models of chondrule formation.

References: [1] Desch and Connolly (2002) *MAPS* 37, 183–207. [2] Hewins et al. (2005) in *Chondrites and the Protoplanetary Disk*, 286–316. [3] Berlin et al. (2011) *MAPS* 46, 513–533. [4] Desch et al. (2012) *MAPS* 47, 1139–1156. [5] Tachibana et al. (2006) *LPSC XXXVII*, #2263. [6] Schrader and Lauretta (2010) *GCA* 74, 1719–1733. [7] Kullerud (1963b) *Ann. Rep. Geophys. Lab.* 1412, 175–189. [8] Schrader et al. (2015) *MAPS* 50, 15–50. [9] Brearley (2006) *MESSII*, 584–624. [10] Kullerud (1963a) *Can. Min.* 7, 353–366. [11] Misra and Fleet (1973) *Econ. Geol.* 68, 518–539. [12] Francis et al. (1976) *Am. Mineral.* 61, 913–920. [13] Etschmann et al. (2004) *Am. Mineral.* 89, 39–50. [14] Schrader et al. (2015) *LPSC XLV*, #1604. [15] Berlin et al. (2008) *Microscopy and Microanalysis* 14, 110–111. [16] Hubbard et al. (2012) *ApJ* 761, 58–69. [17] McNally et al. (2013) *ApJ Lett.* 767, L2. [18] Desch and Turner (2015) *ApJ* 811, 156. [19] Fu et al. (2014) *Science* 346, 1089–1092.