Co-precipitation temperature of olivine and spinel in FeO-rich chondrules inferred from Al-in-olivine thermometry

Takuma Sumitani [1], Kohei Fukuda [1], Willam O. Nachlas [2], Akira Yamaguchi [3], Mingming Zhang [2], Guillaume Siron [4], Makoto Kimura [3], Kentaro Terada [1] and Noriko T. Kita [2]

[1] Osaka University, Japan
[2] University of Wisconsin-Madison, USA
[3] National Institute of Polar Research (NIPR), Japan
[4] University of Bologna, Italy

Introduction: Chondrules in primitive meteorites are key objects for revealing the early evolution of the solar protoplanetary disk. Chondrules formed by a transient heating process in which the precursor material is rapidly heated, melted, and cooled in the disk. However, the mechanism that caused the transient heating process is still controversial. Several candidates for chondrule formation mechanisms have been proposed, with the nebular shock-wave heating model seems currently one of the most favored [1]. In this model, chondrule precursors experienced frictional heating that was induced by passing through the shock-wave in the disk. The shock-wave heating model predicts that the degree of heating of chondrule precursors depends on gas density of the chondrule-forming region and relative velocity between post-shock gas and precursor dust [e.g., 2]. Therefore, the condition of the chondrule formation can be constrained by determining the heating temperature of the chondrule precursor. In this study we applied the Al-in-olivine thermometer, a geo-thermometer for determining the co-precipitation temperature of olivine and spinel [3, 4], to chondrules from pristine ordinary and carbonaceous chondrites. Based on the co-precipitation temperatures as well as chondrule formation ages and oxygen isotope ratios determined from the previous studies, we discuss the spatial and temporal dependence on the condition of chondrule formation in the Solar protoplanetary disk.

Sample and methods: We investigated major and minor element concentrations in chondrule olivine and spinel grains from thin sections of six chondrites [MET 00452 (L/LL3.05), MET 00526 (L/LL3.05), NWA 8276 (L3.00), QUE 97008 (L3.05), DOM 08006 (CO3.01), Acfer 094 (Ungrouped C3.00)]. Analyses of spinel and olivine grains were performed with the JEOL JXA-8200 electron-probe microanalyzer (EPMA) at the National Institute of Polar Research and Cameca SX-Five FE EPMA at the University of Wisconsin-Madison, respectively. Abundances of the elements Na, Ca, Si, Fe, Mn, Ni, Al, Cr, Ca, V, Zn, P, and Ni in Spinel grains were determined by an electron beam accelerated at 15 kV with a beam current of 30 nA. Olivine grains were analyzed by an electron beam accelerated at 20 kV with two different beam conditions and analysis durations. Six elements (Mg, Ca, Si, Fe, Mn, and Ni) were analyzed with a beam current of 20 nA for 30 seconds, while the other three (Al, P, Cr) were analyzed with a beam current of 200 nA for 300 seconds. Aluminum in olivine was measured by three spectrometers simultaneously, and raw counts were aggregated to improve the detection limit (0.0011 wt% Al_2O_3). Reported uncertainties for the calculated temperatures are either 2SE of the calculated temperatures for each olivine-spinel pair in a given chondrule or the uncertainty of empirical calibration for Al-in-olivine thermometry (±25 °C) [3, 4], whichever is larger.

Results: In this study, the occurrence of spinel in chondrules can be divided into three types: (1) small euhedral grains coexisting with olivines, (2) isolated grains in chondrule mesostasis and (3) inclusion with corroded boundaries in olivine phenocryst in chondrules. Mg#s (= [Mg]/[Mg+Fe] in molar %) of olivine grains in chondrules range from 48 to 83, and thus all chondrules studied are classified as type II chondrules (Mg#<90). Al_2O_3 contents of olivine and Cr#s (= [Cr]/[Cr+Al] in molar %) of spinel range from 0.018 to 0.155 wt% and 0.4 to 0.7, respectively. The co-precipitation temperatures of olivine and spinel grains were determined using the Al-in-olivine thermometer for 12 out of 35 spinel grains, which occur as small euhedral grains coexisting with olivines that are interpreted to have co-crystallized in equilibrium with the coexisting olivines. The calculated co-precipitation temperatures of olivine and spinel range from 1273 ± 25 to 1424 ± 25 °C for ordinary chondrite (OC) chondrules and from 1218 ± 129 to 1349 ± 87 °C for carbonaceous chondrite (CC) chondrules.

Discussion: The origins of spinel grains in chondrules are interpreted either as a relict that condensed or crystallized during formation of chondrule precursors such as refractory inclusions or direct crystallization from chondrule melt [e.g., 5, 6, 7]. The relict spinel grains are not interpreted to have achieved equilibrium with coexisting olivines and thus should not be used for the Al-in-olivine thermometry. The chemical compositions of spinel grains could be indicators for distinguishing the two scenarios [6]. For example, the Cr_2O_3 concentrations of the spinel grains in the chondrules studied are distinct (>30 wt%) from those of spinel grains in refractory inclusions (<1 wt%; [e.g., 8, 9]), suggesting that the spinel grains measured in this study crystallized from the chondrule melt rather than relicts of refractory inclusions.

The oxygen isotope ratios of some of the chondrules studied here have been determined to be $-2.8‰ < \Delta^{17}O < 0.4‰$ (where $\Delta^{17}O = \delta^{17}O - 0.52 \times \delta^{18}O$) [10, 11, 12]. Among them, the oxygen isotope ratios of the OC chondrules are systematically depleted in ^{16}O ($-0.3‰ < \Delta^{17}O < 0.4‰$) relative to those of the CC chondrules ($-2.8‰ < \Delta^{17}O < -2.0‰$), indicating that these chondrules formed in the inner and outer Solar System, respectively [10, 11, 12]. The range of the co-precipitation temperatures of olivine and spinel in the OC and CC chondrules studied here are consistent with each other, suggesting that the lower limit of heating temperatures for chondrule formation are similar in both the inner and outer Solar System. The Al-Mg ages of the chondrules discussed here have also been determined to be ~1.8–3.0 million years after the formation of Ca-Al-rich inclusions (CAIs) [10, 11, 13-15]. By combining the Al-Mg and oxygen isotope data as well as co-precipitation temperatures, we constrain that heating mechanisms with the temperature above 1200 °C are required for type II chondrule formation in the inner and outer Solar System during the period of ~1.8–3.0 million years after CAI formation. Co-precipitation temperatures of olivine and spinel in type I (Mg#>90) chondrules from CV3 chondrites have been investigated by using the Al-in-olivine thermometer [16]. The calculated temperatures for the type I chondrules range from 1200 to 1640 °C, slightly more variable than those determined for type II chondrules here (1218 ± 129 to 1424 ± 25 °C), but the lower limit of the temperature for type I chondrules (~1200 °C, [16]) is consistent with our estimate for CC (1218 ± 129 °C) and OC (1273 ± 25 °C) chondrules. These observations indicate that the lower limit of the chondrule formation temperature should be higher than 1200 °C for both type I and II chondrules.

Acknowledgement: We thank ANSMET Program and the Smithsonian Institution, National Museum of Natural History, for providing meteorite thin sections.

References: [1] Desch et al (2012) MAPS 47, 1139-1156. [2] Iida et al (2002) Icarus 153, 430-450. [3] Wan et al (2008) Am. Min. 93, 1142-1147. [4] Coogan et al (2014) Chem. Geol. 368, 1-10. [5] Sheng et al (1991) GCA 55, 581-599. [6] Kimura et al (2006) GCA 70, 5634-5650. [7] Zhang et al (2020) GCA 272, 198-217. [8] Ma et al (2008) LPSC 39, 23-56, #2030. [9] Rudraswami et al (2011) GCA 75, 7596-7611. [10] Siron et al (2021) GCA 293, 103-126. [11] Siron et al (2022) GCA 324, 312-345. [12] Fukuda et al (2023) JpGU meeting, PPS08-P10. [13] Ushikubo et al (2013) GCA 109, 280-295. [14] Hertwig et al (2019) GCA 253, 111-126. [15] Zhang et al (2022) Chem. Geol. 608, 121016. [16] Schnuriger et al (2022) MAPS 57, 1018-1037.