AL-MG CHRONOLOGY OF ANORTHITE-BEARING CHONDRULES FROM UNEQUIVOCATED ORDINARY CHONDRIRES: CLUES ON SHORT DURATION OF CHONDRULES FORMATION. G. Siron\textsuperscript{1}, K. Fukuda\textsuperscript{1}, M. Kimura\textsuperscript{2}, and N.T. Kita\textsuperscript{3}.\textsuperscript{1}WiscSIMS, University of Wisconsin-Madison, Madison, WI 53706, USA (siron@wisc.edu), \textsuperscript{2}National Institute of Polar Research, Tachikawa, Tokyo 190-8518, Japan.

Introduction: The timing and duration of chondrule formation is a key information for the dynamical evolution of the early solar system. Chondrules in ordinary chondrites are considered to form within a short duration (\( \leq 0.1 \) Ma) [1, 2], which would prevent a large extent of mixing of materials in the protoplanetary disk [3]. The \(^{26}\text{Al}/^{26}\text{Mg}\) chronology (\( \Delta t_{1/2} = 0.705 \text{ Ma} \)) is a powerful means to determine relative ages of chondrules precisely [4]. While an earlier study on ferromagnesian chondrules in unequilibrated ordinary chondrites (UOCs) by [5] shows a short duration of their relative formation ages (<1 Ma), recent studies [6, 7] indicate a longer duration (~1.5 Ma).

Our goal is to determine the UOC chondrule ages with higher precisions (<0.1 Ma) than previous studies by taking advantage of the RF (radio-frequency) Plasma Ion Source at the WiscSIMS IMS 1280 that allow smaller and denser primary beam [8, 9]. Here we focus on anorthite-bearing chondrules in UOCs with low subtypes (3.01-3.05 [10]) to avoid resetting of the chronometer due to parent body metamorphism [4].

Sample and methods: 14 chondrules were selected from 5 UOCs for the study; 4 from QUE 97008 (L3.05), 4 from NWA 8276 (L3.05), 2 from NWA 8649 (LL3.05), 2 from Semarkona (LL3.01) and 2 from MET 00452 (LL3.05). Mineral chemistries were determined prior to SIMS analysis using EPMA.

Oxygen three isotopes and Al-Mg isotopes were analyzed using WiscSIMS IMS 1280 [e.g., 9, 11]. Oxygen three-isotope analyses of olivine, pyroxene, and plagioclase were obtained using 12 \( \mu \text{m} \) spots (2.5 nA) on multi-Faraday cup (FC) with a reproducibility (2SD) better than 0.3\%o for \( ^{16}\text{O} / ^{18}\text{O} \) and \( ^{17}\text{O} / ^{16}\text{O} \). Mg isotope analyses of plagioclases were measured using a 0.2 nA \( \text{O}^+ \) primary beam (diameter ~6 \( \mu \text{m} \)) with Faraday cup (FC) and electron multipliers (EMs) for simultaneous detection of \(^{24}\text{Mg} \) and \(^{25,26}\text{Mg} \) isotopes, respectively, which provide a precision 0.4-0.7\%o \( ^{26}\text{Mg}^* \). A few chondrules were also analyzed using 4 nA primary beam (15 \( \mu \text{m} \)) with multi-FC detectors with precisions ~0.4\%. Mg isotope analyses of olivine and pyroxene were obtained using a 1 nA primary beam (8 \( \mu \text{m} \)) on multi-FC with reproducibility of ~0.05\%o for \( ^{26}\text{Mg}^* \). For each chondrule, 5-8 analyses of O isotopes, 6-12 plagioclase and 4 olivine/pyroxene analyses of Mg isotopes were obtained. Details of SIMS Al-Mg analytical conditions are described in [12].

Results: The olivine and pyroxene Mg\# (molar [MgO]/[MgO+FeO] \%) are between 76 and 97 and are generally in good agreement inside each chondrule. No secondary zoning was observed in olivine compositions. Plagioclase compositions are very close to pure anorthite with only two chondrules below An\textsubscript{95} (An\textsubscript{94} and An\textsubscript{93}). Their MgO contents range is 0.5-1.0\%, indicating high CaMgSi\textsubscript{2}O\textsubscript{6} component in plagioclase. Mean plagioclases compositions from all chondrules exhibit silica excess, similar extents to those in CR chondrites and Acfer 094 [11], except for NWA 8649. Most of these chondrules resemble clast chondrule in [13] and FeO-rich (type II) plagioclase bearing chondrules in [14]. They show a wide range of Mg\# and are depleted in Na compared to majority of type-II chondrules in UOCs [14].

The mean oxygen ratios of individual chondrules are shown in Fig. 1, which are similar to previous data from LL3.0-3.1 chondrules [14]. Anorthite-bearing chondrules plot closer to TFL (terrestrial fractionation line) with \( ^{17}\text{O} / ^{16}\text{O} \) from ~0.4 %o to ~0.5 %o. Oxygen isotope ratios in plagioclase were obtained from three chondrules and they are in good agreement with those of olivine and pyroxene in the same chondrule.

![Fig. 1. Mean oxygen three-isotope ratios of individual anorthite-bearing chondrules in this study. Reference lines (ECL, PCM, CCAM) are from [15-17].](image-url)

All chondrules exhibit resolvable \( ^{26}\text{Mg}^* \) in plagioclases with \(^{27}\text{Al} / ^{24}\text{Mg} \) ratios between 33 and 75. All chondrules but one show well-behaved \(^{26}\text{Al} / ^{24}\text{Mg} \) isochron data (MSWD: 0.37-1.8) with \(^{26}\text{Al} / ^{27}\text{Al} \) between (6.3±0.7)×10\textsuperscript{-6} and (8.9±0.3)×10\textsuperscript{-6}. Examples are shown in Fig. 2. One chondrule from NWA 8649 show a significant scatter in \( ^{26}\text{Mg}^* \) and with a MSWD value of 4.7, so that the inferred \(^{26}\text{Al} / ^{27}\text{Al} \) was not determined for the chondrule. Formation ages are calculated relative to CAIs between 1.80 ± 0.04 Ma and 2.16 ±
0.11 Ma by assuming homogeneous distribution of 
$^{26}$Al with $(^{26}\text{Al}/^{27}\text{Al})_0 = 5.252 \times 10^{-5}$ at $t=0$ \[18\]. The relative ages calculated for two chondrules separately 
by using Multi-FC and FC-EM plagioclase data gave 
consistent ages within errors (Fig. 3). The mean relative 
ages of 13 chondrules are $1.9 \pm 0.1$ Ma (SD, n=13). Chondrules in QUE97008 gave systematically 
younger ages (2.0-2.2 Ma) than the rest of chondrites 
(1.8-2.0 Ma). No difference in chondrule ages between 
chondrule groups (L vs LL) nor chondrule types (I vs II) 
are found (Fig. 3). We do not find systematic 
changes in $\Delta^{18}$O with ages.

![Figure 2. Example of isochron $^{26}$Al-^{26}Mg diagrams for three chondrules.](image)

**Discussion:** The presence of excess silica for plagioclases in almost all chondrules and well-behaved 
$^{26}$Al-^{26}Mg isochron (MSWD–1) are good indicators that the extent of parent-body metamorphism was 
not significant. Additionally, the consistency between FC-
FC and FC-EM determined ages highlight the accuracy 
of the present analytical methods. Therefore, the robust 
and high precision (<0.1 Ma) $^{26}$Al-^{26}Mg relative ages 
clearly show that UOC chondrule formation lasted less 
than 0.4 Ma and did not exceed 2.2 Ma after CAIs. 
This range is in agreement with the peak value of the 
oldest ages among UOC chondrules determined by \[6\] 
and \[7\], respectively. Thus, our new dataset from the 
anorthite-bearing chondrules may represent the age 
distribution of UOC chondrules in general. Based on 
small uncertainties of the relative ages, at least two or 
possibly more episodes of chondrule formation 
ocurred over a duration of 0.4 Ma. Ages of the youngest 
two chondrules form QUE97008 (c143 and c150) are 
resolved from those of eight older chondrules beyond 
their uncertainties. Relative ages of other chondrules 
range from 1.8 Ma to 2.0 Ma with significant error 
overlap. However, data from several chondrules are 
clearly distinguished beyond the uncertainties. There 
seems to be no clear gap(s) in the distribution of relative 
ages.

![Figure 3. Inferred ($^{26}$Al/$^{27}$Al)$_0$ and relative ages after CAIs for the studied chondrules.](image)

**Implication:** New high precision SIMS $^{26}$Al-$^{26}$Mg 
data clearly show that the timescale for UOC chon-
drule formation was much shorter than previously re-
ported \[6-7\]. The short duration of these chondrule 
ages suggests that disk radial transport was very lim-
lit for the L/LL chondrite forming regions \[3\]. New 
dataset highlight that the timescale is longer than 0.1 
Ma, in contrast to the prediction from the extremely 
high dust density for chondrule formation \[1\].

Abstract #2213. [9] Hertwig et al. (2019) GCA, 253, 111-
55, 2317-2337. [16] Ushikubo T. et al. (2012) GCA, 90, 