

OXYGEN ISOTOPES OF CHONDRULES IN THE QUEEN ALEXANDRA RANGE 99177 CR3 CHONDRITE: FURTHER EVIDENCE FOR SYSTEMATIC RELATIONSHIPS BETWEEN CHONDRULE MG# AND $\Delta^{17}\text{O}$ AND THE ROLE OF ICE DURING CHONDRULE FORMATION. T. J. Tenner¹, D. Nakashima¹, T. Ushikubo¹, N.T. Kita¹, and M.K. Weisberg^{2,3}, ¹WiscSIMS, Department of Geoscience, University of Wisconsin-Madison, USA (tenner@wisc.edu), ²Kingsborough Community College and Graduate Center, CUNY, USA, ³American Museum of Natural History, NY, USA.

Introduction: Chondrules are a major component of primitive chondrites and their spehrulitic and igneous textures indicate heating and crystallization of precursor material. In type 2/type 3 CO, CR, and Acfer 094 ungrouped C chondrites, chondrules vary greatly in the Mg# (Mol. % MgO/{MgO + FeO}) of their respective olivines/pyroxenes (35-100) [1-5], implying significant variability in oxygen fugacity during chondrule formation [6] and potential variability of the Fe concentration of their precursor materials. Oxygen isotope ratios of these chondrules are equally interesting; those with Mg#>s > 97 are ¹⁶O-rich, with $\Delta^{17}\text{O}$ ($=\delta^{17}\text{O}-0.52\times\delta^{18}\text{O}$) values ranging from ~-4 to -6 ‰. In contrast, Mg# < 97 chondrules have $\Delta^{17}\text{O}$ values ranging from -2 to 1 ‰ [1-5]. A recent study of Meteorite Hills (MET) 00426, a CR3 chondrite, showed a continuous trend in chondrule $\Delta^{17}\text{O}$, from -6 to -1 ‰, as individual chondrule Mg# decreased from 99 to 94 [7]. Overall, these observations suggest that the processes controlling the oxygen fugacity during chondrule formation ultimately affect chondrule oxygen isotope ratios. In this study, we further investigate this phenomenon by analyzing chondrules from the Queen Alexandra Range 99177 (QUE) CR3 chondrite.

Samples and Methods: 19 chondrules were selected for O-isotope analysis based on 1) chondrule Mg#, and 2) analyzable anorthite by SIMS for future ²⁶Al-²⁶Mg chronometry. Chondrule Mg#>s range from 95 to 99. No type II chondrules/fragments were found

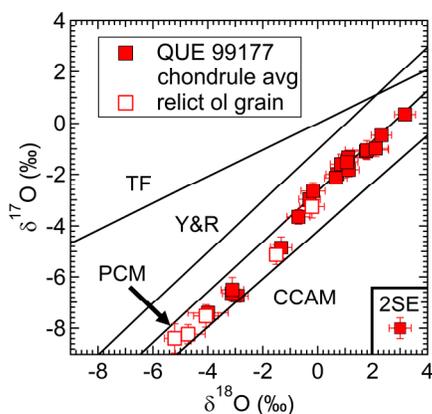


Fig. 1: Oxygen 3-isotope plot of QUE 99177 chondrules and relict grains. Each solid symbol represents the average of individual SIMS measurements per chondrule. Open symbols are single measurements of relict olivine grains.

in the section. BSE and SEI images were collected with a Hitachi S-3400N SEM. Major element concentrations of phases were measured with a Cameca SX51 EMP. Oxygen 3-isotope ratios of olivine, pyroxene, and plagioclase within chondrules were measured with the WiscSIMS Cameca-IMS 1280 ion microprobe, configured with multi-collector Faraday cups as detailed in [8]. Using a primary Cs⁺ ion intensity of 2.6 nA, spot sizes were $15 \times 10 \mu\text{m}$. External reproducibilities (2SD) were 0.4, 0.4, and 0.4 ‰ for $\delta^{18}\text{O}$, $\delta^{17}\text{O}$, and $\Delta^{17}\text{O}$, respectively, based on bracketing measurements of San Carlos olivine. 179 SIMS analyses of chondrules were acquired, with 6 to 14 analyses per chondrule.

Results and Discussion: Oxygen isotope ratios of chondrules are between the CCAM [9] and Young and Russell [10] lines; many lie on the PCM [5] line (Fig. 1). 5 olivine grains from 4 chondrules indicate isotopically relict material because they exceed the 3SD $\Delta^{17}\text{O}$ external reproducibility (0.6‰) when compared to the average $\Delta^{17}\text{O}$ of all other spot measurements within a chondrule. Relicts are ¹⁶O-rich compared to respective “host” chondrule oxygen isotope ratios, but are within the range observed in other chondrules (Fig. 1).

Origin of olivine in QUE 99177 chondrules: Recent studies suggest that Mg-rich olivines in chondrules are relicts, originating from a limited number of differentiated planetesimals early in the protoplanetary

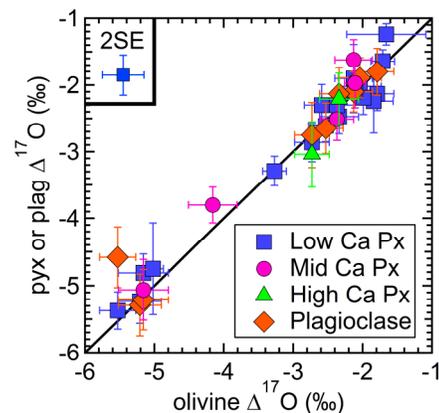
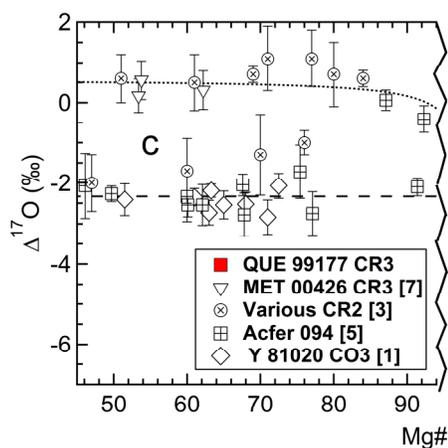


Fig. 2: Comparison of $\Delta^{17}\text{O}$ of averaged olivine (excluding relict grains; Fig. 1) to coexisting averaged pyroxene and/or plagioclase in QUE 99177 chondrules, illustrating a 1:1 relationship (solid black line). This indicates that olivine, pyroxene, and plagioclase crystallized co-magmatically.

disk [11,12] prior to the final chondrule melting event. If true, one would expect a lack of correlation in $\Delta^{17}\text{O}$ between olivine and other coexisting chondrule phases (which presumably crystallized from the final chondrule melting event). However, $\Delta^{17}\text{O}$ values of olivine and coexisting pyroxene/plagioclase in QUE 99177 chondrules exhibit a 1 to 1 relationship (Fig. 2), implying that nearly all analyzed olivines (82 of 87) crystallized upon cooling in the final chondrule melting event. Similar results were found in primitive CO, Acfer 094, CR, and CV chondrites [1,5,7,13].

Relationship between Mg# and $\Delta^{17}\text{O}$: Mg# 99 chondrules have $\Delta^{17}\text{O}$ values of ~ -5 ‰, and with decreasing chondrule Mg# $\Delta^{17}\text{O}$ values continually increase (Fig. 3). There are 2 distinct trends: one that increases to -2.3 ‰ and one that increases to -1 ‰ at a chondrule Mg# of 97. These trends are more apparent when Acfer 094, CO, and other CR chondrite data are included, extending to Mg# < 50 (Fig. 3). What does this mean? Assuming Mg# 99 chondrules formed in a highly reduced [6] and an implied anhydrous environment, their precursors had a $\Delta^{17}\text{O}$ of ~ -5 ‰ (Fig. 3 “a”). Addition of positive $\Delta^{17}\text{O}$ H_2O [14] to this precursor material would readily change the O-isotope composition upon chondrule heating [15], and oxidize the environment ($\log f_{\text{O}_2}$: -12 to ~ -10.5 ; [6]), yielding Mg# 99 to ~ 95 chondrules [6,16] with increasingly positive $\Delta^{17}\text{O}$ values (Fig. 3 “b”). Differences in the $\text{H}_2\text{O}/\text{dust}$ ratio in precursors, or 2 distinct $\Delta^{17}\text{O}$ H_2O reservoirs may explain 2 trends. Mg# < 90 chondrules have near-constant $\Delta^{17}\text{O}$ values in respective trends (Fig. 3 “c”), meaning that the $\text{H}_2\text{O}/\text{dust}$ ratio is constant in respective trends. Variable Fe enrichment of precursor material and/or progressive $\text{H}_2\text{O}/\text{dust}$ enrichment could explain the wide range of chondrule Mg#'s, the latter process yielding more oxidized conditions ($1000\times$ solar system dust enrichment $\approx \log f_{\text{O}_2}$: $-9 \approx$ Mg# 70 chondrules; [16]) during chondrule formation.



The implied constant $\text{H}_2\text{O}/\text{dust}$ ratio in the Mg# 45-90 chondrule forming environment allows for estimation of the $\Delta^{17}\text{O}$ of H_2O ice in precursor material. Assuming anhydrous precursor material had a $\Delta^{17}\text{O}$ of -5 ‰ (Fig. 3 “a”) and that the amount of H_2O in precursors necessary for forming Mg# < 90 chondrules yields a $\sim 1:1$ ratio of oxygen between H_2O and anhydrous precursor material [17], the Mg# 45-90 chondrule $\Delta^{17}\text{O}$ trends (-2.3 and 0.5 ‰, respectively; Fig. 3 “c”) constrain H_2O ice $\Delta^{17}\text{O}$, from 0.5 to 6 ‰.

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Fig 3: QUE 99177 chondrule Mg# versus $\Delta^{17}\text{O}$, and comparison to chondrules in other carbonaceous chondrites. Averaged olivine and low-Ca pyroxene Mg# represent the chondrule Mg#. Note the difference in the Mg# scaling between the left and right panels. QUE 99177 chondrules follow 2 separate trends, which are more apparent when combined with Mg#/ $\Delta^{17}\text{O}$ values of other studies. Explanations of trend shapes (i.e. a, b, and c) are described in the text.

