

**Reassembled but not quite the same chondrules.  
R- and OC-chondrite chondrules:  
Oxygen-isotope studies of PRE 95404,15**

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**Introduction:** Rumuruti chondrites (R chondrites) are in some respects “extreme” or “unusual” among the current chondrite collections (as summarized in a review by [1]). R chondrites share some properties both with ordinary chondrites (OC) and with carbonaceous chondrites (CC). R chondrites (along with CK carbonaceous chondrites) constitute one of the two most oxidized chondrite groups. R chondrites are characterized by low chondrule/matrix modal abundance ratios (0.9 in unbrecciated Carlisle Lakes), moderate chondrule sizes (~400  $\mu\text{m}$ ), abundant sulfides (typically 6-10 wt.% pyrrhotite and pentlandite), rare refractory inclusions (~0.04 vol. %) and high  $\Delta^{17}\text{O}$  values (~2.9‰).

The high bulk  $\Delta^{17}\text{O}$  values of R chondrites and their chondrule sizes and textural types are similar to the properties of ordinary chondrites. In contrast, the high matrix abundance of R chondrites resembles that of carbonaceous chondrites. The mean bulk R-chondrite  $\Delta^{17}\text{O}$  value of ~3‰ is the highest among chondrite groups and the most anomalous  $^{16}\text{O}$ -poor oxygen isotope composition across planetary materials as compared to that of the Sun. Most R whole rocks have similar  $\Delta^{17}\text{O}$  values. The O-isotopic compositions of chondrules scatter around a mass-fractionation line with  $\Delta^{17}\text{O} = \sim 3\%$ ; however, chondrules from Carlisle Lakes and PCA 91241 plot close to the OC region:  $\Delta^{17}\text{O} = 0.68\%$  [2]; and -0.4 to 0.7‰ [3], respectively. Most individual olivine and pyroxene grains in R chondrites plot near an R-chondrite mass-fractionation-line (RFL), defining the intercept ( $\Delta^{17}\text{O} = \sim 3\%$ ), or in the region of unequilibrated ordinary chondrites (UOC) [3]. A few refractory forsterite grains in DAG 013 have low  $\Delta^{17}\text{O}$  values of about -3‰ [4]. Most individual minerals in most R-chondrite CAIs plot along a slope-1 line and have lower  $\Delta^{17}\text{O}$  values in the range of -23‰ to -26‰ [5].

Previous hypotheses concerning R-chondrule formation held that their precursors had OC-chondrule O-isotopic compositions that later acquired higher  $\Delta^{17}\text{O}$  values by reaction with nebular gas [2] or water derived from parent body fluids associated with the matrix [3]. Despite their accuracy, bulk R-chondrule O-isotope data are not ideal for testing these hypotheses because they lose the specific information as many chondrule mesostases were altered by  $\Delta^{17}\text{O}$ -rich parent-body fluids. It is a more direct approach to approximate the original O-isotopic compositions of R-chondrule precursors by using *in situ* analyses of olivine phenocrysts in minimally altered R chondrules. To help understand R-chondrite formation we obtained oxygen isotopes and composition data for mafic minerals in R3.6 PRE 95404. We compare our results with data collected from SIMS analysis on olivine phenocrysts in chondrules from several other chondrite groups.

**Sample analyses:** Backscattered electron (BSE) and cathodoluminescence (CL) images were taken. Individual chondrules and olivine/pyroxene fragments were examined using a LEO 1430 scanning electron microscope (SEM) equipped with monochrome CL, a VEGA Tescan SEM equipped with color CL and energy-dispersive X-ray spectroscopy (EDX), and the JEOL 8200 electron microprobe at UCLA. Secondary ion mass spectrometry (SIMS) analyses were performed on the UCLA 1270 ion microprobe using a primary  $\text{Cs}^+$  beam and analyzing negative secondary ions.

**Results and discussion:** The O-isotopic compositions found for the interiors of some R-chondrite chondrule olivine phenocrysts have high  $\Delta^{17}\text{O}$  values that are similar to that of R-chondrite whole rocks (+3‰) suggesting that the precursors of chondrules with these O-isotopic compositions already existed when R chondrules formed. We also find that the chondrule populations have a wide diversity in oxygen-isotope compositions that can be quantified by a standard measure of population entropy. Many chondrules are unequilibrated but some are equilibrated. Our data show that  $\Delta^{17}\text{O}$  values in PRE 95404 are similar to those in Semarkona, but those in the R chondrite record more extreme values (both high and low). Olivine compositions range from Fa0 values typical of type-I chondrules to Fa40 values typical of equilibrated R chondrites; there is no correlation between the Fa value of olivine and the  $\Delta^{17}\text{O}$  value. However, Fa values and  $\delta^{18}\text{O}$  exhibits a weak correlation among  $^{16}\text{O}$ -depleted chondrules ( $\Delta^{17}\text{O}$  values > -1). Fe-poor olivine phenocrysts have O-isotopic compositions that are significantly lighter; some data are plotted on the left of the Y & R line [6] on the three O-isotope diagram. These mass-

dependently light O-isotope compositions are also observed in olivine phenocrysts of type-I chondrules in LL chondrites [7]. Our data and the SIMS data from [7] suggest that these isotopically light composition had established before or during the chondrule formation. These SIMS results indicate that the O-isotope compositions of bulk R chondrite chondrules [2] that are also lighter than Y & R line likely reflect isotopically light olivine compositions. Thus, the isotopic compositions cannot be attributed only to parent-body alteration such as isotope exchange between mesostasis and fluid.

Petrographic observations of PRE 95404,15 indicate that type R3 chondrites consist of a mixture of chondritic components metamorphosed to different degrees and embedded in fine grained matrix that appears rather pristine (c.f. Allende matrix [8] Fig. 4). The existence of equilibrated and intact chondrules and unequilibrated chondrules within a few mm of each other suggests that the final consolidation of PRE 95404 occurred later than the metamorphism of at least some parts of the R-chondrite parent body (or bodies) and perhaps after the metamorphism of some ordinary-chondrite parent bodies. Although the R-chondrite group is heavily brecciated, there is a lack of impact annealing or strong compaction unlike that in most equilibrated OCs. The some equilibrated olivine fragments and igneous sulfide nodules found in the matrix of PRE 95404,15 appear to be “post-accretionary” fragments.

**Summary:** We measured the O-isotopic compositions of R-chondrite chondrules and olivine fragments. Most of the O-isotopic compositions of R-chondrite chondrules (including previous data) show that there are variations among OC and R whole rock regions. Chondrules with  $\Delta^{17}\text{O} \sim 3\text{‰}$  in olivine can be Fe-poor in composition. This implies that high- $\Delta^{17}\text{O}$  R-chondrite chondrule precursors existed prior to chondrule formation and that previous hypotheses of R-chondrule formation invoking reaction with nebular gas [2] or with water derived from parent-body fluids [3] are unlikely. The diversity of the silicate precursors of R chondrules is larger than that in OCs in terms of  $\Delta^{17}\text{O}$  values. Along with previous observations and based on our new data, we conclude that it is possible that the R-chondrite parent body was larger or that it accreted from planetesimals formed later than those of ordinary chondrites. Further observations and geochronological research are required to quantitatively test the timing of rock formation. From the observations of the diverse thermal histories across the chondritic components, the final lithification of R3 chondrites (formation of type-3 rocks) occurred later than R-chondrite whole-rock metamorphism.

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